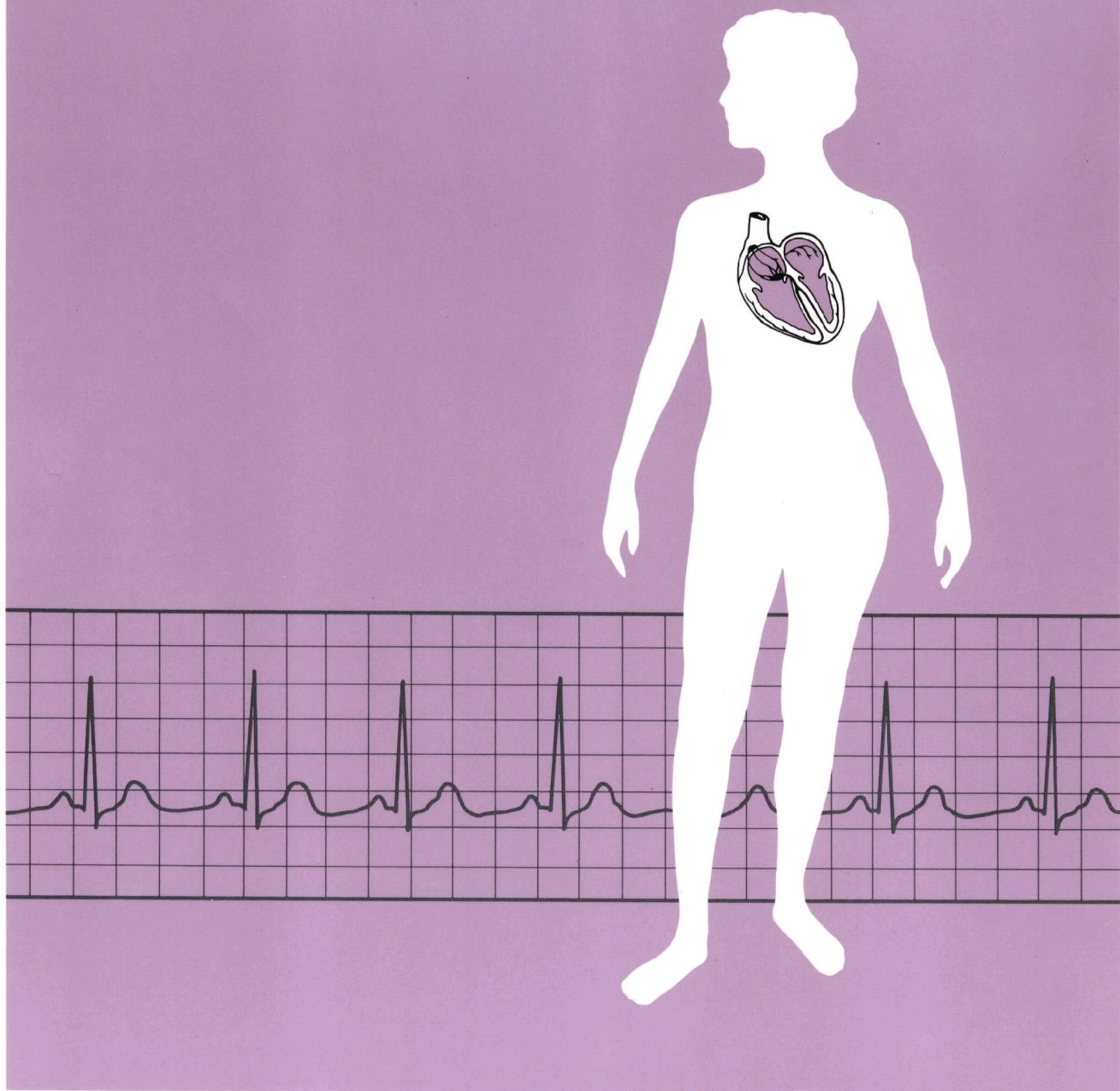


S p a c e l a b s M e d i c a l

BIOPHYSICAL MEASUREMENT SERIES

ELECTROCARDIOGRAPHY



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ELECTROCARDIOGRAPHY

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INTRODUCTION

Understanding the generation of electrocardiographic signals and the production of electrocardiograms requires appreciation of certain electric and cardiac fundamentals. Those fundamentals appear in Section 1.0, Some Fundamentals of Electricity, and Section 2.0, Cardiac Cells. Section 3.0 presents models of the human heart that are especially helpful in relating the waves, intervals, and segments in electrocardiograms to electric activity in specific regions of the heart.

Section 4.0, Traditional Electrocardiographic Voltages, and Section 5.0, Nontraditional Electrocardiographic Voltages, classify and explain various electric signals pertaining to the heart. A brief caution on obtaining signals from inside the body precedes the description of traditionally important voltages available on the skin. Among such voltages are those of the 12-lead system and various systems used for monitoring. The examples of lead-systems, body-surface potential maps, and certain electrograms emphasize that electrocardiac signals are present everywhere on and in the body.

Mathematic analysis of the signals provides information helpful in the design and testing of electrocardiographic amplifiers and displays. The method described in Section 6.0, Characteristics of Electrocardiographic Signals, involves the Fourier series, which divulges the constant and the sinusoidally alternating components of periodic waves. Specification of the bandwidth of an electrocardiograph results from careful application of the Fourier concept.

Obtaining the signals to be amplified and displayed is the topic of Section 7.0, Electrodes and Electrolytes. Electrodes must be chemically, mechanically, and biologically safe, besides being electrically effective. The electrolytic medium between each electrode and the skin decreases the impedance but increases the risk of allergic reaction and chemical irritation.

Section 8.0, Amplifiers, describes amplification of electrocardiac signals and specifies several ways to ensure electric safety despite all the connections. Linearity, bandwidth, input impedance, and common-mode rejection are the other topics in the section.

Displaying the amplified signal is the main subject in Section 9.0, Displayers. Oscilloscopes allow short-term displays, but produce no record unless a camera is used. Devices such as chart recorders and x-y plotters provide the usual records. Some equipment can render traces in

various colors, on screen or paper. Devices such as laser printers can produce high-resolution traces and notes on pages of paper or transparent plastic.

Each topic in Section 10.0, Miscellaneous Concepts, pertains to electrocardiography, by tradition or extension. An example is axis deviation, which relates to the cardiac dipole, an oversimplification of the electric activity of the heart. Vectorcardiography attempts to define the three-dimensional movement of the tip of the cardiac dipole vector by projecting the movement onto various planes. High-resolution electrocardiography, which depends on scalar instead of vector methods, seeks information in very small voltages pertaining to the electric activity of the heart.

The signals that are generated, obtained, amplified, and displayed need analysis and interpretation to be useful. Rate, rhythm, and shape are prime considerations in Section 11.0, Information From Electrocardiographs, which includes a set of guidelines for clinical interpretation of electrocardiograms.

1.0 SOME FUNDAMENTALS OF ELECTRICITY

1.1 *Definition*

Electricity is a phenomenon of matter: the atoms in matter have components, such as protons, that manifest electric properties. That definition refers to atomic constituents of all substances, whether gaseous, liquid, or solid. Defining electricity as a class of energy generated in certain ways is equally valid, but not so universal. Citing the perceptible effects of electricity, such as the sight, sound, and smell that accompany sparking, leads to an empirical definition, but the group of effects would hardly define the entity itself.

1.2 *Electric Charge and Field*

Electric charge is that property of matter responsible for the various electric phenomena. The classifications of charge, positive and negative, however, are remarkably arbitrary. Negative charge is that which would repel amber (a resinous material) after it has been rubbed with wool. Positive charge is that which would repel a glass rod after it has been rubbed with silk.

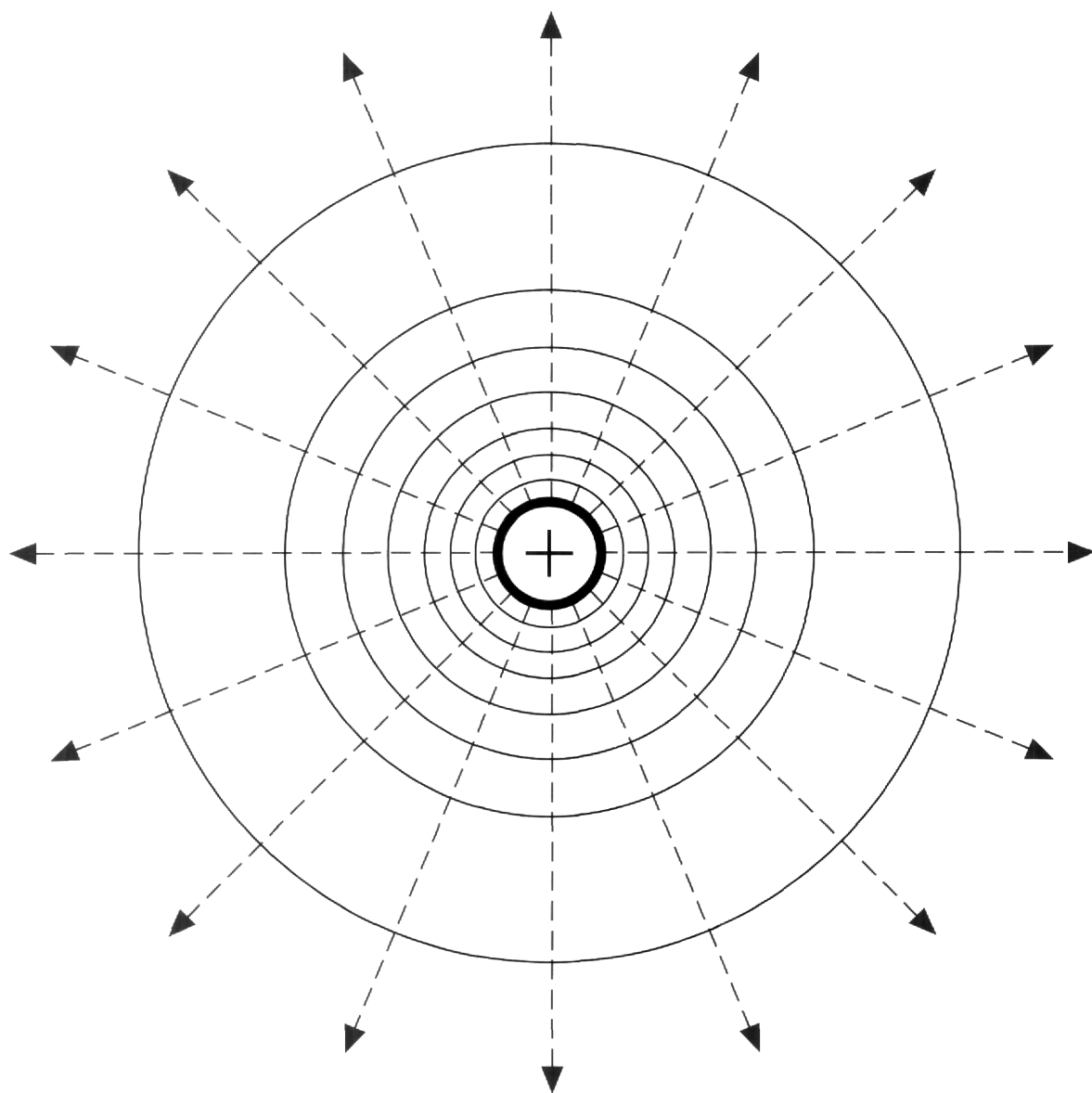
In chemistry, a demonstration of polarities involves cations and anions. In life science, certain ions, such as Na^+ , Ca^{++} , and Cl^- , exhibit polarity. In clinical medicine, the term electrolytes refers to ionic, therefore charged, constituents of blood. Charged entities, by whatever name, have polarities that fundamentally relate to the directions of the electric force impressed on other charges.

Force is one of the basic phenomena associated with charge. Two like charges repel each other, and two unlike charges attract each other. If two particles with charges Q_1 and Q_2 are separated by distance R , the force F between them, by Coulomb's law, is directly proportional to the product of the charges and inversely proportional to the square of the distance between the charged particles, that is:

$$F = K \frac{Q_1 Q_2}{R^2}$$

Equation 1.1

Figure 1.1 — Lines of electric force (dashed lines) and equipotential contours (solid lines) pertaining to a charged particle alone in space that is the same throughout.



where F = force, in the direction specified on page 3
 K = constant, for the medium and the system of units
 Q_1 = charge of particle 1
 Q_2 = charge of particle 2
 R = distance between the particles.

Because distance R is multiplied by itself in the denominator, the force diminishes rapidly as the two charged particles are separated. The direction of the force would be along a straight line joining the two particles, and would depend on the polarity of each charge.

If the particle with charge Q_2 were completely removed from the space in which the particle with the charge Q_1 resides, Q_1 would still affect the space by providing a field. Anytime the particle with Q_2 returned to the space, it would meet a force predictable by Coulomb's law. This mathematic expression for the force is a simple modification of Equation 1.1, to emphasize electric field intensity E :

$$F = Q_2 E \quad \text{Equation 1.2}$$

where F = force, in the direction specified above
 Q_2 = charge of particle 2
 E = electric field intensity $K Q_1 / R^2$, where K , Q_1 , and R are as defined for Equation 1.1.

A charge causes an electric field, which causes a force on any other charge in that field. If both Q_1 and Q_2 were positive, moving Q_2 from one point to another that is closer to Q_1 would require work. That work for each unit of positive charge is the potential difference, or voltage, between the two points.

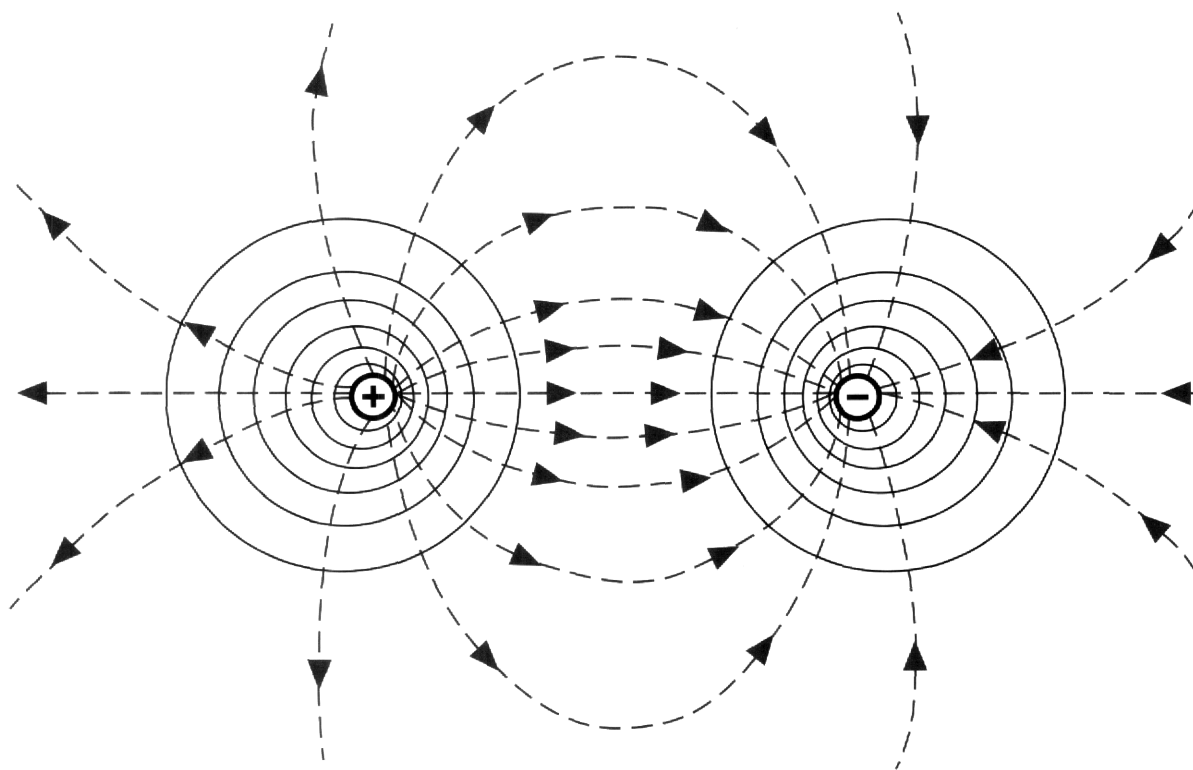
One notation for the voltage between points a and b is V_{ab} , which can be either positive or negative depending on the direction of the electric field. The first letter in the double subscript denotes the point assumed to have the higher potential. If work must be done to move unit positive charge from point a to point b , the direction of the field must be away from point b , which means that the charge there is more positive than that at point a . Voltage V_{ab} must, therefore, be negative in that situation; V_{ba} , positive.

Figure 1.1 depicts the direction of the electric field of a positively charged particle alone in space. The lines of electric force (dashed lines) are in the direction of the force that a positive charge would undergo if it

were placed in the field. If all possible locations of the test charge were considered, the lines would fill the page. In a three-dimensional figure, the lines of force would radiate outward in all directions from the charged particle.

The solid lines in Figure 1.1 illustrate the concept of equipotential, or isopotential, surfaces. Again, the figure is necessarily two-dimensional, representing just one plane in a three-dimensional situation. At each point on an equipotential surface, the potential measured with respect to a common reference point is the same as that measured at any other point on the contour.

Figure 1.2 — Lines of electric force (dashed lines) and equipotential contours (solid lines) pertaining to an electric dipole.



1.3 ***Electric Dipole***

Figure 1.2 illustrates what happens to the electric field and equipotential contours when a second particle exists in the considered space. The second particle has a charge of equal magnitude but opposite polarity. Separated, the two charges form a dipole. The lines of electric force are

not simply radial, as they were for the single charge, and the equipotential contours are not circles having the charge at the center. Further distortion of the lines and contours would take place if other charges were added to the system and if the space were not the same throughout.

1.4 **Current**

Current is the movement of charge. Voltage between two points can produce a current if the medium between the points has less than infinite resistance. Ohm's law applies, and this equation is a mathematic statement of it:

$$v = ir \quad \text{Equation 1.3}$$

where v = voltage
 i = current
 r = resistance.

Equation 1.3 has lower-case letters because variables v , i , and r represent instantaneous voltage, current, and resistance. Upper-case letters would denote either constant or root-mean-square voltage, current, and resistance. Because the electricity relevant to electrocardiography varies considerably through small fractions of a second, reference to instantaneous values is appropriate. A common letter for voltage in the equation for Ohm's law is e , but that letter could be confusing inasmuch as it could be considered the instantaneous value of electric field intensity E , previously described. The units of the parameters are volts, amperes, and ohms, for v , i , and r , respectively. Conductivity g , which is the reciprocal of resistance, is occasionally the quantity of interest. The unit of conductivity is the mho or siemen.

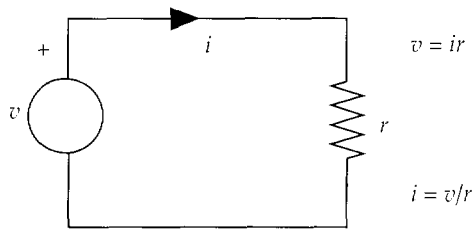
1.5 **Capacitance**

Capacitance is the proportionality constant that relates charge to voltage. The equation is:

$$C = Q/V \quad \text{Equation 1.4}$$

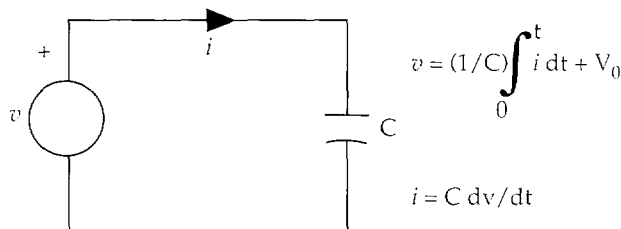
where C = capacitance
 Q = charge
 V = voltage.

Figure 1.3 — Schematics and equations pertaining to purely resistive and purely capacitive circuits.



At any instant, the voltage v across a resistance r is proportional to the current "through" the resistance at that instant.

At any instant, the current i "through" a resistance r is proportional to the voltage v across the resistance at that instant.



The voltage across capacitance C at any instant t is proportional to the time-integral of the current i that went "through" it, added to the initial voltage V_0 on the capacitance.

The instantaneous current i "through" capacitance C is proportional to the rate of change of voltage v across the capacitance at that instant.

If a device can accept and hold a charge, it will have a voltage. The charge establishes an electric field, and work is necessary in moving charge within the field. The work is voltage, by definition.

Capacitance exists when two conductors are separated by less conductive material. The separating material must be nonconductive if the capacitor is to retain charge for a long time. Retention of charge is just one capability of a capacitor; another capability is displacement of charge. Charge accumulating on one conductor produces a field that forces charge of the same polarity on the other conductor to move away if a conductive path exists to permit the displacement. Movement of charge to one conductor causes movement of charge from the other. The capacitor thus seems to allow current through it, despite the insulation between the two conductors. That current, referred to as displacement current, is proportional to the rate of change of the voltage: the faster the change, the greater the current.

When the voltage across a capacitance is steady, the current is zero. Capacitance resists an instantaneous change in voltage and so provides a kind of voltaic inertia. The voltage across a capacitance does not change instantaneously because the needed charge would have to be accumulated in zero time. Figure 1.3 shows the circuit, equations, and symbol for capacitance in relation to the circuit, equations, and symbol for resistance.

1.6 ***Relevance to Life Science***

Concepts such as charge, polarity, electric field, and voltage are fundamental to the study of electricity, and electricity is fundamental to life. The cell, which is a basic component of living things, sustains a voltage, often called a cell potential, because of a special arrangement of charges on each side of the membrane. The charges cause an electric field in the membrane; therefore, polar materials in the membrane endure an electric force.

The movement of ions through a cellular membrane is essentially current through a resistance. Some cellular current is steady, yet some is transient, occurring only upon stimulation of the membrane. Different ions traverse at different times, so terms such as “sodium current” and “potassium current” are common in the literature of life science. The transient voltage, called an action potential, contains contributions of the voltage developed by the various and varying currents and resistances. Some of the action potential pertains to a different variable, capacitance.

A common model of a living cell includes a capacitance to account for certain ionic situations and movements. Models of the cardiovascular system, moreover, have capacitance to represent vascular elasticity. Analogous to the storage of mechanical energy by the elastic fibers of an artery is the storage of electrical energy by a capacitor.

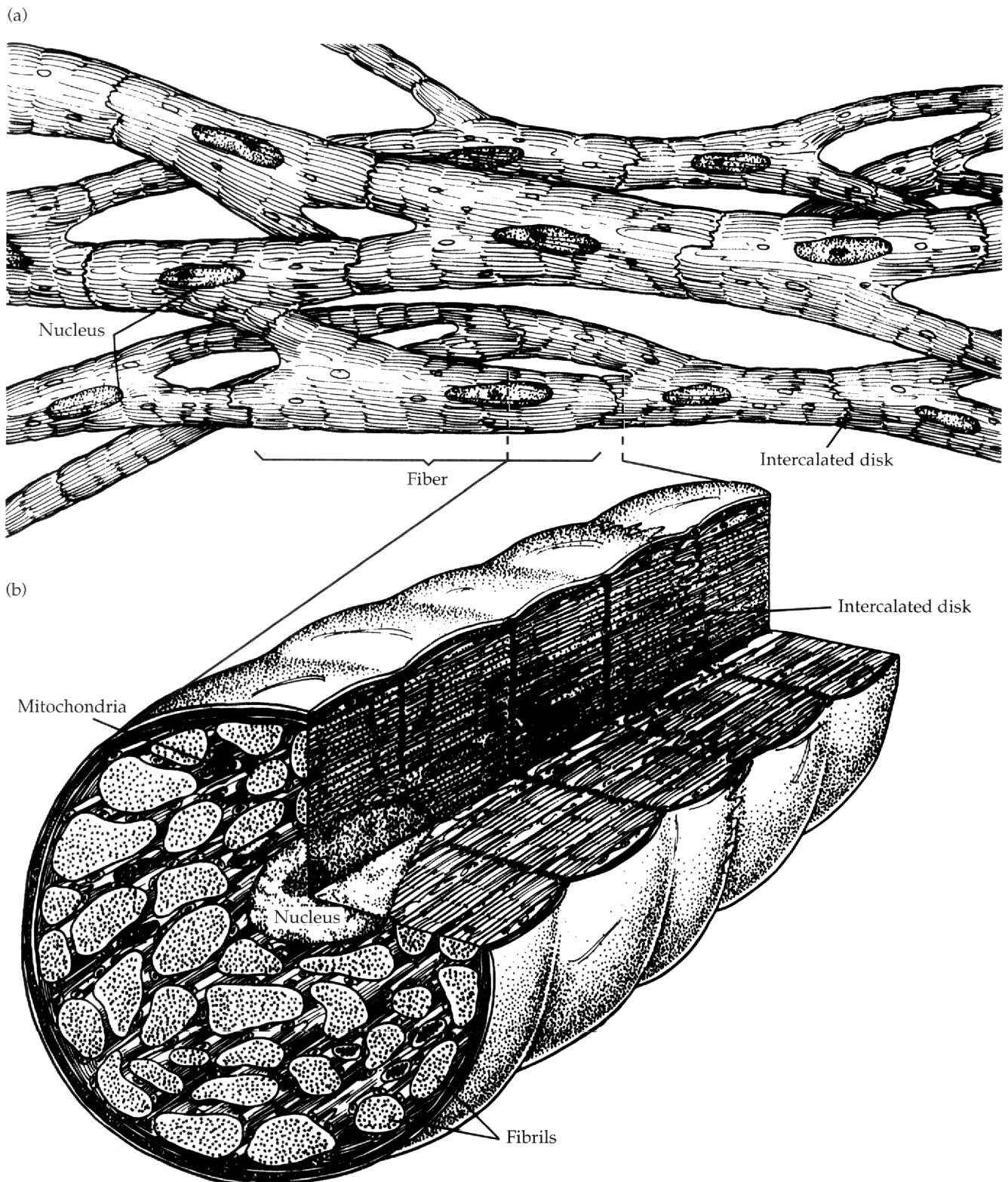
2.0 **CARDIAC CELLS**

2.1 ***Cellular Form and Function***

The human heart has hundreds of thousands of cells, each a kind of microscopic bag in which some chemicals exist in water. Each cell is a complex system with characteristics and performances that contribute to cardiac function. The foremost function is, unquestionably, the coordinated contraction, or the “beating,” of the heart.

Many cells participate in cardiac contraction, with different groups of cells doing so in different phases of the contraction. Because electrocardiographic signals result from all ionic movement pertaining to numerous cells of the heart, specific and direct relations of the signals to the changing voltage of a single cell, or to an algebraic summation of the action potentials of any pair of cells, are obscure. The voltage of a stimulated cell contributes to the electrocardiogram, but merely as the shout of one person in a crowded stadium contributes to the roar.

Figure 2.1 — Generalized cells of the human heart:
(a) Chain of fibers. (b) Magnified view of a section
near an intercalated disk.



Cells of various groups in a heart are somewhat different from one another in anatomy and physiology. Even so, a generalized cell, or fiber, of the heart can be representative (see Figure 2.1a). A microscopic view of the inside of the fiber (Figure 2.1b) includes many contractile filaments in bundles. Mechanically and electrically connecting one fiber to another is a double-layered membrane called an intercalated disk. At various locations in each disk are "gap junctions," which are especially conductive electrically. The cell is rich in mitochondria, which are the major developers of the chemical adenosine triphosphate, the principal source of energy in the cell.

2.2 Cellular Electrochemistry

2.2.1 Voltage of a Resting Cell

Chemical reactions inside and outside the cell provide mobile ions, and a small number of them move through the membrane. The ease of passage, called permeability, varies for different ions, hence the term selective permeability.

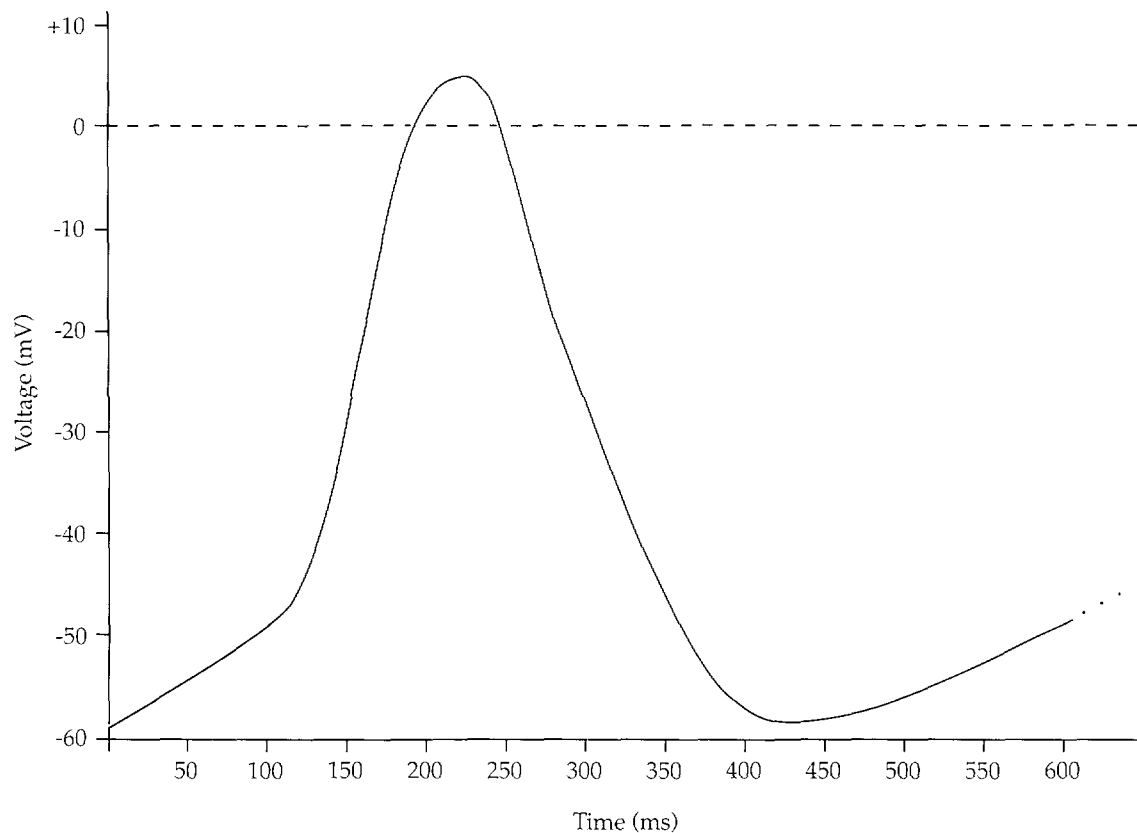
Although the membrane of a resting cell severely limits passage of sodium ions, it just moderately limits passage of potassium ions. Much more ionized sodium exists in extracellular fluid than in intracellular fluid, but the membrane is usually an effective, although leaky, barrier. When the membrane is stimulated, permeability to sodium ions increases considerably. Sodium ions that enter the cell are few in comparison with the large quantity in the extracellular and intracellular fluids. The entering quantity is enough, however, to change certain cellular activities significantly.

Inside the resting cell the ratio of potassium ions to sodium ions is high. Upon stimulation of the cell, some potassium ions exit just after sodium ions enter. A common theory holds that the ions of sodium and potassium are the most important in cellular electrochemistry. Among other positive ions that participate are calcium and magnesium; among the negative ions are chloride and bicarbonate. Recent research and clinical experience confirms the importance of calcium ions in the permeability of the membrane of cardiac cells. Drugs called "calcium blockers" have been remarkably successful in modifying the electric activity of the heart.

The imbalance of ions across the membrane of a resting cell is an imbalance of electric charge. An electric field and voltage exist, therefore,

across the membrane. Because the direction of the electric field is from outside to inside the cell, the polar materials in the membrane sustain a directional force. That force changes in magnitude and direction when the cell is stimulated. The voltage, often called the resting potential of the cell, changes when the imbalance changes, as when the membrane is stimulated. For a generalized cell of the heart, the resting voltage is 50 to 100 millivolts, measured across the membrane, from the outside to the inside. The voltage from the inside to the outside of the cell, measured across the membrane, is thus a negative voltage of the same amount. A ventricular cell at rest has a voltage typically higher than that of an atrial cell at rest. Because ventricular cells definitely outnumber those of the atria, the transmembrane voltage usually assigned to a generalized cell of the heart is -90 millivolts.

Figure 2.2 — Action potential of a cell of the SA node.



2.2.2 Action Potential

The membrane of certain cardiac cells permits a significant leak of sodium ions from the extracellular fluid. That process eventually alters the voltage enough that the membrane allows passage of more ions. The channels through which the additional ions travel in the membrane are the so-called slow calcium-sodium channels, which allow only slow passage of ions. Meanwhile, the permeability for potassium ions gradually increases, allowing more of them to exit the cell. The rising part of the wave of voltage (Figure 2.2) across the membrane is not so steep as that pertaining to skeletal muscle, which has sodium channels that open much faster.

During the next phase of ionic movement, slow channels for calcium and sodium ions close, but channels for potassium ions open further. The departure of more potassium ions from inside the cell helps considerably in restoring the transmembrane voltage to the resting level.

To send some sodium ions back through the membrane and to bring back some potassium ions, the cell must expend energy. The exact means for moving ions out of and into the cell is still in debate. Electrochemical evidence supports the concept that an ionic pump helps in the creation and maintenance of the ionic concentrations responsible for the resting voltage, with selective permeability playing the major role.

The traditional name for the entire excursion of voltage is action potential (Figure 2.2). A remarkably descriptive term for an action potential measured against a time-base with large increments is spike.

Cells of the type described earlier in this section are especially fast in producing action potentials repeatedly. A long-term record would show a series of spikes with essentially the same interval between them. The cells produce action potentials automatically, so one term for the characteristic is automaticity. Another term is autorhythmicity, which emphasizes the periodic feature. The cells of the sinoatrial (SA) node normally produce action potentials at a rate higher than that normally possible by other cells of the heart. The SA node is thus the usual pacemaker. Nerve endings in and near the SA node issue chemicals that change its rate of production of action potentials. Other substances such as catecholamines and certain ions in the blood serving the node modify the rate too. The temperature of the node is yet another influence on the rate.

Certain cells of the heart normally produce action potentials only after a depolarizing stimulus starts the ionic process. Upon such stimula-

Figure 2.3 — Action potential of a cell from a cardiac ventricle, in relation to changes in the permeability of certain ions. (Notations: sodium, Na^+ ; potassium, K^+ ; calcium, Ca^{++})

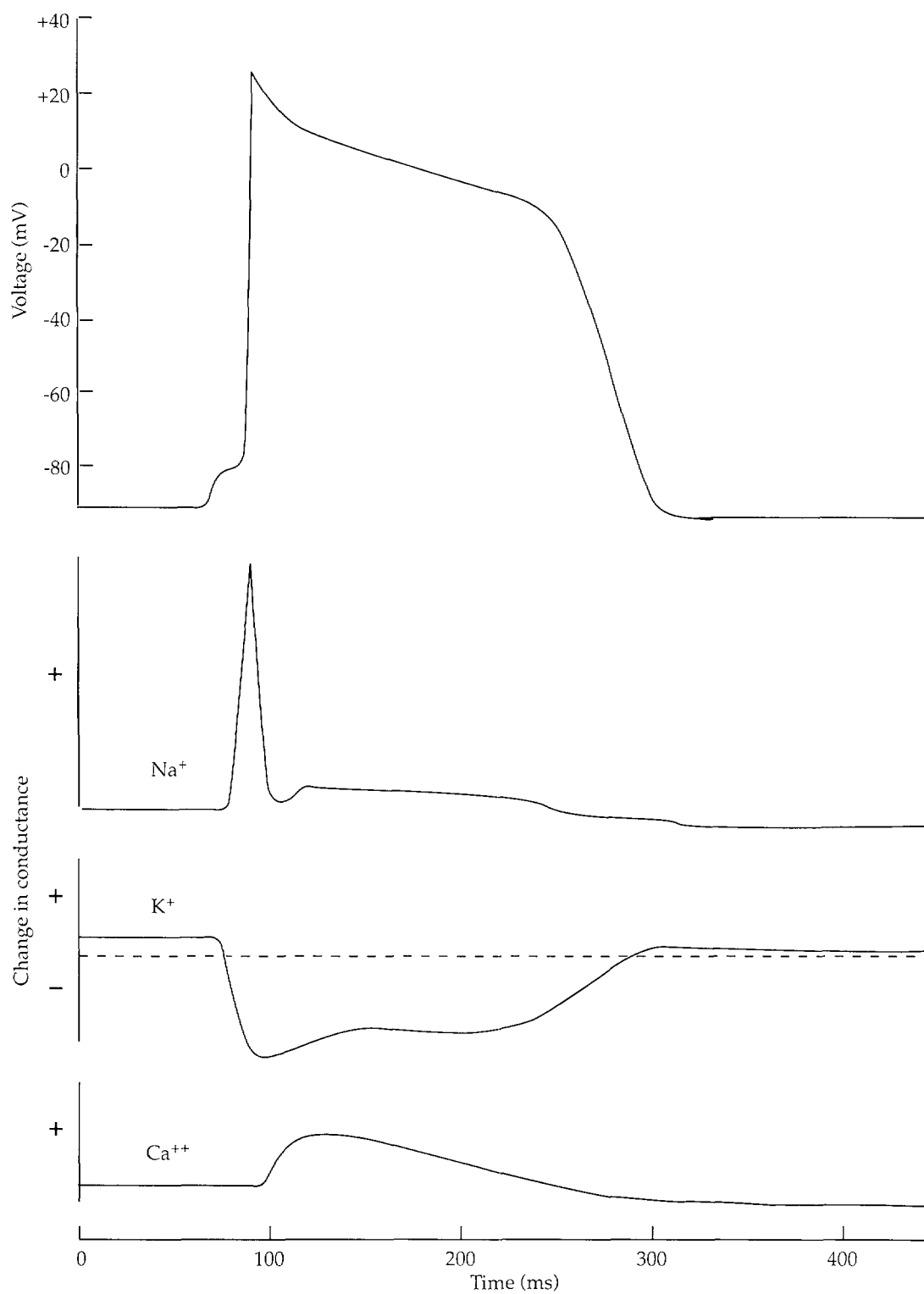


Figure 2.4 — Action potentials of cells of various regions of the heart.

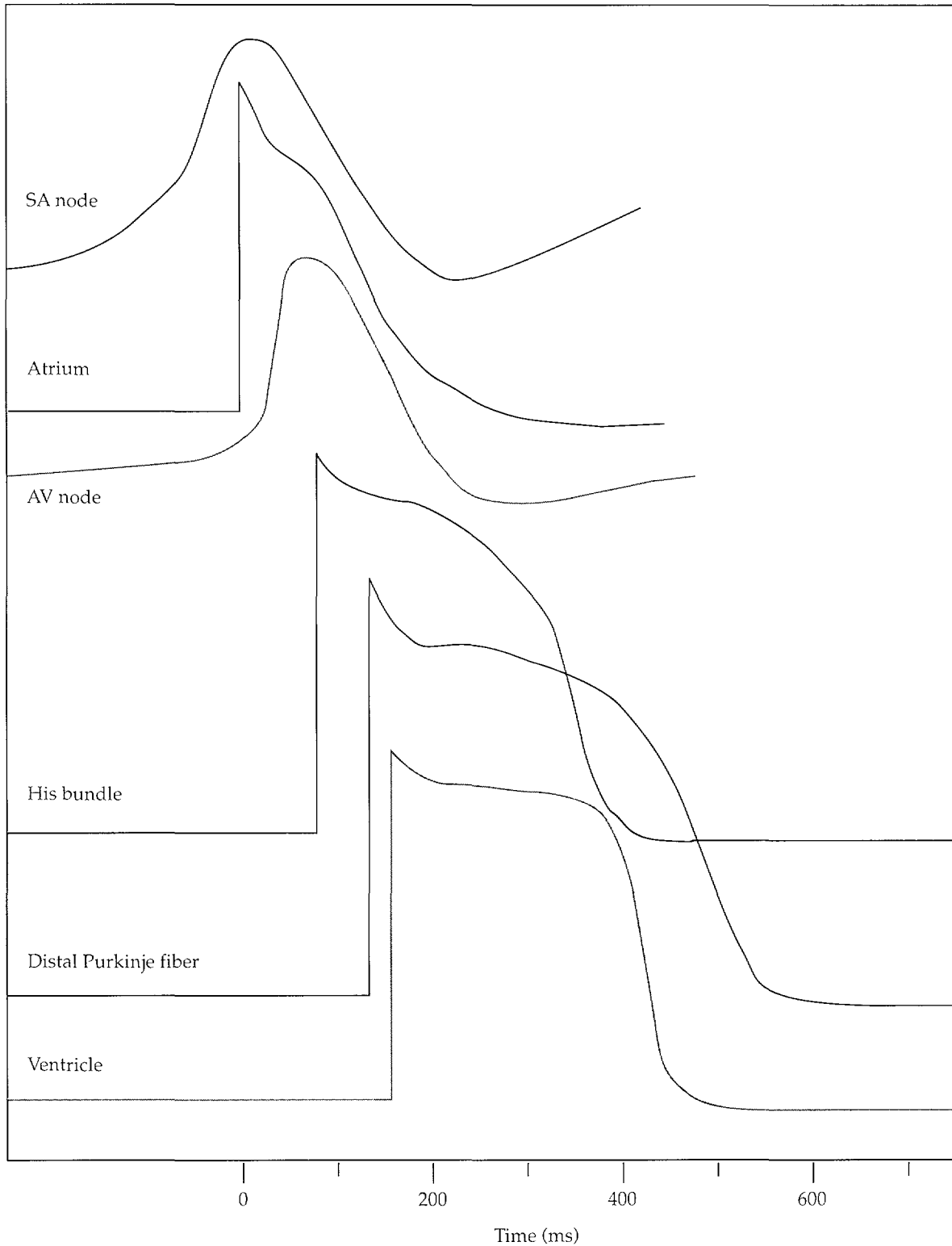


Figure 2.5 — Various periods pertaining to an action potential.

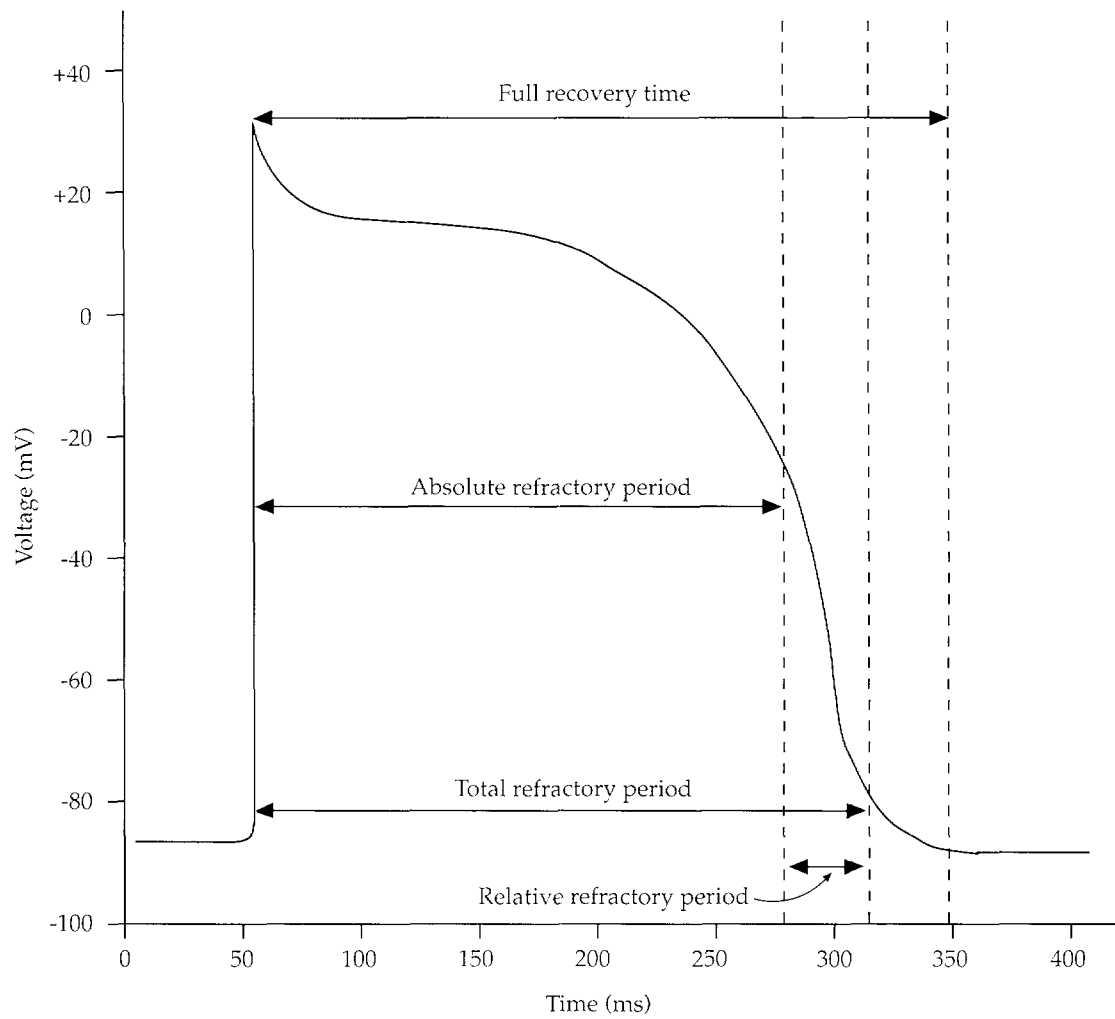
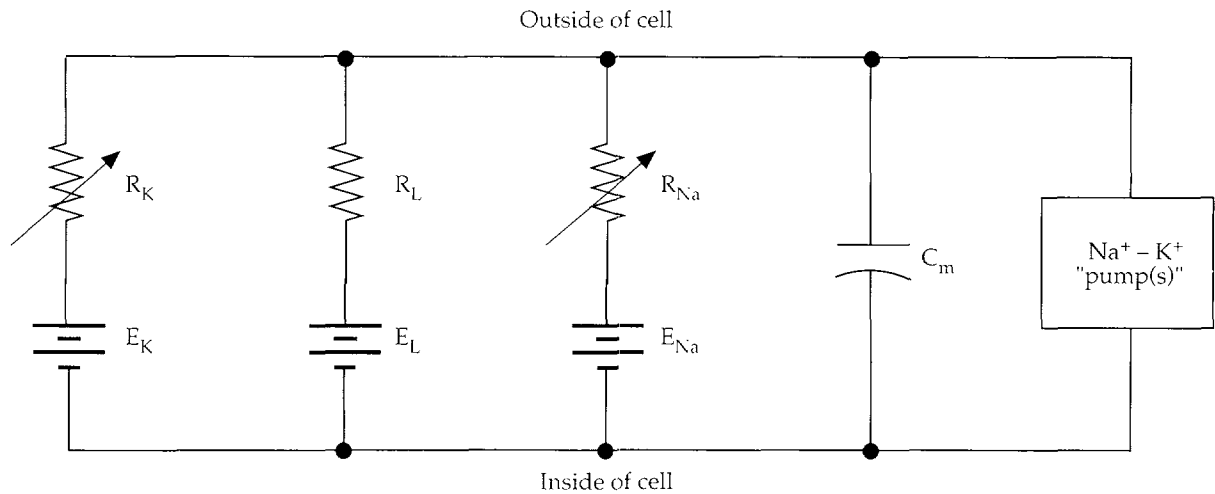


Figure 2.6 — Electric model of a cell.



tion, the membrane of a cell of that type changes permeability to sodium ions abruptly, by opening so-called fast channels. The depolarization proceeds quickly, so the wavefront of the cellular voltage is steep (Figure 2.3). The almost flat portion of the wave relates to the decrease in permeability for potassium ions. The inside of the cell then has so much positive charge, owing to the potassium ions and the sodium ions, that the voltage remains for a while at a level higher (less negative) than the resting voltage. Repolarization after that so called plateau is swift; the wave decays rapidly to the resting voltage.

Cells in various parts of the heart have membranes with different permeabilities and different changes in permeabilities. The action potentials are thus different. Figure 2.4 offers an array of typical waves, each from a cell representing those in certain parts of the heart. Each action potential of each cell normally leads to contraction of the cell. The coordinated contraction of numerous cells causes beating of the heart.

2.2.3 Refractory Period

If a stimulus that caused a cell to produce an action potential were reapplied too soon, it would have no appreciable effect. During much of the action potential, the cell is immune to stimulation, that is, the cell is in what is called the absolute refractory period (Figure 2.5). Later in the wave is an interval called the relative refractory period, in which a stimulus larger than the one that initiated the response can cause an action potential. Another way to provoke an action potential from a cell during its relative refractory period is to stimulate it repeatedly. Sequential stimulation even with pulses at the intensity of the stimulus that first caused the cell to produce an action potential can be effective during the relative refractory period.

2.3 Electric Model

Figure 2.6 presents an electric model proposed by Hodgkin and Huxley. Although designed to represent a neural cell, it applies generally to a cardiac cell. Of primary significance is the capacitance, which represents the two conductors (the extracellular fluid and the intracellular fluid) separated by an insulator (the membrane). A remarkably good dielectric, the membrane of a cardiac cell at rest withstands a field equivalent to millions of volts per meter.

Capacitance requires time to accumulate charge. Any abrupt change in voltage across a capacitor requires a large current. Slower changes in the capacitor's voltage require less current. Experimental data on the movements of ions through the membrane support the concept of capacitance, whether variable or constant, in the model. The concepts of fast and slow channels for ions are compatible with the model, as well.

The battery pertaining to the sodium ions is in series with the pertinent conductance, as is the battery pertaining to potassium ions. The third battery and conductance shown in Figure 2.6 pertain to all other ions capable of moving through the membrane. Like any other model, the one in Figure 2.6 can be overextended and misunderstood. Without all the specifications and assumptions at hand, a person could expect, for example, the battery pertaining to sodium ions to drive current through the battery pertaining to potassium ions.

Analog and digital computers continue to be useful in modeling the circuits and the coupled equations pertaining to cellular activity. Several models, or simulations, have caused reconsideration of some concepts and redirection of certain efforts in cellular research.

3.0 ELECTRIC MODELS OF THE HUMAN HEART

3.1 *General Model*

If each cell in the heart could be adequately modeled by a circuit such as that presented in Section 2.0, Cardiac Cells, and if all those circuits could be properly interconnected, an electric model of the heart would result. That model would be difficult to comprehend, however, because of its dimensions and interconnections. A computer would certainly be useful because of the size of the model. Simulation of just a portion of the ventricular myocardium as an interconnected system of thousands of circuits, each representing a cell, might provide new information, especially if the simulation involved adaptive processing.

3.2 *Specific Model*

A model that refers to groups of cells instead of individual cells variously interconnected must suffice until a general model is developed. A common model treats the heart as a system composed of a generator

and many conductors. The generator is the SA node, and the major conductors are the special paths in the heart. Because all the components in the circuit are biologic, the complexity is greater than that of a circuit of comparatively simple, purely electric components. Biologic components often operate nonlinearly, even in their normal ranges, and they are adaptive.

3.2.1 Generator

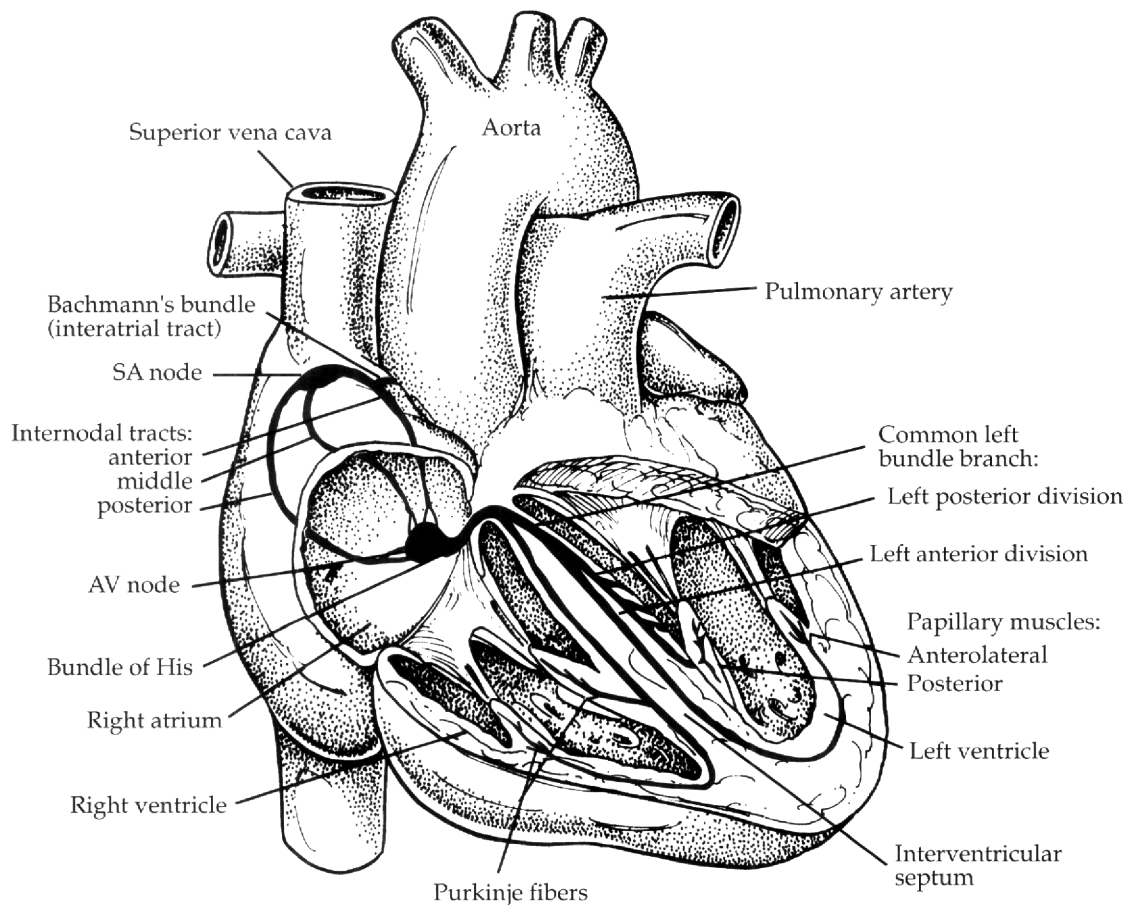
The SA node is the normal generator. That node, or mass of specialized cells, exists near the top of the rear of the upper chamber of the right side of the heart, that is, in the superior region of the posterior portion of the right atrium. At the core of the node are P cells that automatically produce action potentials at a rate normally higher than that of any other cell or group of cells in the heart.

Hardly autonomous in setting the heart rate, the SA node dispatches action potentials at a rate modified by some nerves and by certain substances in the blood. The free-running rate of the SA node is higher than its controlled rate. Much control depends on fibers of the vagus nerve, which is a parasympathetic cranial nerve. The chemical output at the ends of the vagal fibers can change the ionic permeability of the cellular membranes and cause a decrease in the rate of impulses from the node. Fibers from the sympathetic division of the nervous system control antagonistically their chemical output and cause an increase in the rate of impulses. Various substances in the blood affect the local chemistry, so they, too, can change the rate. The hormone norepinephrine, for example, causes an increase in rate. The SA node, so controlled, serves as the usual pacemaker.

3.2.2 Atrial Paths of Enhanced Conduction

The “wave of depolarization” travels away from the SA node more quickly through certain paths in the atria than through the other cells in those parts of the heart. In effect, a depolarizing wave speeds along those paths, which are considered functional rather than histologic, from the SA node to the atrioventricular (AV) node. Cells alongside the paths depolarize as the wave travels by, and they relay the wave to neighboring cells. Atrial contraction ensues, and the blood lingering in the atria then moves promptly to the ventricles. Much of the blood delivered to

Figure 3.1 — Nodes and some paths of conduction in the human heart.



the atria would have already moved to the ventricles, so atrial systole merely provides what is sometimes described as topping off.

Figure 3.1 illustrates three paths of enhanced conduction in the right atrium: the anterior, middle, and posterior tracts. The left atrium receives an interatrial tract, often called Bachmann's bundle, branching from the anterior tract in the right atrium. Activation of the right atrium occurs before that of the left atrium; the activation is asymmetric. The estimated speed of atrial activation is 80 to 100 centimeters per second. The time required for activating the atria is normally 70 to 100 milliseconds.

Published evidence and postulation has led to the naming of additional tracts of the atria. Some of those tracts are within an atrium, some between the atria, some between an atrium or the AV node and a ventricle, and some in circuits involving several cardiac components. The lit-

erature maintains, however, that the preferential paths of normal conduction between the SA node and the AV node are the anterior, middle, and posterior tracts and their ramifications. Anomalous paths, such as the James bundle, the Kent bundles, and the paraspecific fibers of Mahaim, may be involved in abnormal conduction, as in the pre-excitation, or Wolff-Parkinson-White syndrome.

3.2.3 Another Node in the Circuit

The location of the AV node is the posterobasal region of the interatrial septum, between the medial leaflet of the right AV (tricuspid) valve and the orifice of the coronary sinus (Figure 3.1). Electrophysiologists often divide the AV node into three functional regions: the atrio-nodal (AN), nodal (N), and nodal-His (NH). Each region contributes to the functions of the node: receiving the wave of depolarization, delaying it, and dispatching it to the AV bundle.

Anatomists have shown that neural fibers terminate near and in the atrial end of the AV node. Those fibers are from the sympathetic and parasympathetic divisions of the nervous system, akin to those that terminate at the SA node. The outputs of the fibers can modify the chemical environment of the cells of the node and so change their refractory periods. Cells in the nodal region have refractory periods that are remarkably long; an impulse arriving too soon after another would thus encounter a block. Shortening the refractory period allows the AV node to accept a physiologic increase in the rate of impulses from the SA node, as in exercise and various emotional states. Impulses otherwise arriving at a high frequency would encounter a block of some degree. The only electric entrance to the ventricular tracts is normally the AV node because the fibrous skeleton between the atria and ventricles is relatively nonconductive.

The AN, or junctional, part of the AV node can become the pacemaker if the SA node fails. The heart rate in AN pacing is lower than that in SA pacing: 80 beats per minute in contrast to 40 beats per minute, for example. One former name of that condition is nodal rhythm; a current name is junctional rhythm. Certain characteristics in the electrocardiogram help differentiate the low rate of junctional cause from the low rate, or bradycardia, of other causes.

Passage of an impulse through the AV node is somewhat slow: 1 to 10 centimeters per second. The speed is lowest in the AN region and

highest in the NH region of the node. Blood in the atria thus has more time to move in response to atrial contraction and to flow to the ventricles in preparation for ventricular contraction. Artificial, electronic pacemakers programmed to stimulate the atria as well as the ventricles separate the stimulations by about 120 milliseconds, to provide the delay normally afforded by the AV node. Such “dual-chambered pacing” can increase cardiac output over that obtained by purely ventricular pacing.

In the NH region of the AV node are fibers that form the origin of the AV bundle, often called the bundle of His. Conduction speed in the NH region is higher than that in the other two regions of the node. The speed of conduction in the AV bundle itself is even higher, approximately 150 centimeters per second.

3.2.4 More Paths of Enhanced Conduction

After leaving the AV node, the bundle penetrates the ventricular septum and divides into two main branches, the right and left, which serve the respective ventricles. Branching continues on each side, and the ends of the final branches touch the Purkinje network. The network, which consists of Purkinje and transitional fibers, connects to the muscle fibers of the ventricles. An impulse leaving the AV node normally travels to the ventricular musculature through the circuit just outlined, to provoke ventricular systole. If the SA node and the AV node fail, the His-Purkinje system can assume the role of pacemaker, and the heart rate would fall to about 20 beats per minute.

The Purkinje network is asymmetric. In the posterobasal region of the left ventricle, for example, are relatively few Purkinje fibers and transitional cells. The network serves remarkably asymmetric chambers, the outer walls of which have different thicknesses. The normal thickness of the outer wall of the left ventricle is approximately three times that of the right ventricle. Cells of the right and left ventricles are essentially the same size, so the left ventricle has considerably more cells.

The model just described includes, in the normal sequence of excitation: the SA node, atrial tracts, AV node, AV bundle (bundle of His), bundle branches, and Purkinje network. Although the model describes the main circuitry of the heart, it obscures the effects of the hundreds of thousands of other cardiac cells. Modeling the heart as an electric system is, therefore, merely to illustrate, not to define.

4.0 TRADITIONAL ELECTROCARDIOGRAPHIC VOLTAGES

4.1 *Signals Obtained Inside the Body*

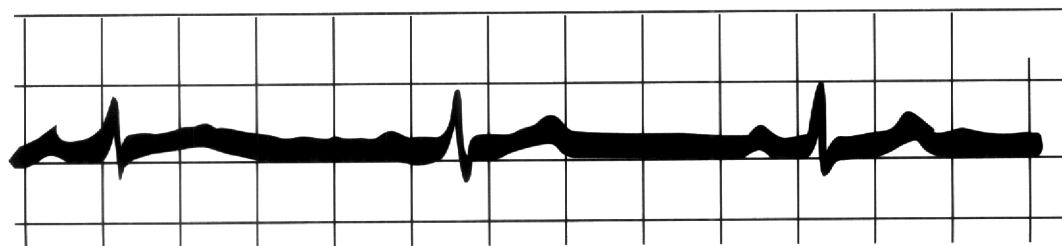
Each action potential of a cell is an electric signal that provides important information about the health of that cell. A running record of action potentials of several thousand cells, in certain parts of the heart, would provide important information about cardiac health. Attaching electrodes directly to the heart, however, would require thoracic surgery. Impaling each selected cell even in a stilled heart would require special equipment, supernatural talent, and considerable time. If the heart could be restarted afterward, its beating could ruin the placement of the electrodes. Measuring thousands of electric signals at the cellular level is plainly prohibitive, although potentially informative.

Measurement of the composite signal, however, of an identified group of cells, such as the SA node, is practical. A small tube, or sensing catheter, maneuvered by way of the venous system to the proper place in the right atrium can have two electrodes near its tip, so that the effect of the electric activity in and very near the SA node can be detected locally. The technique has merit in electric terms, because the signal loses strength and gains noise, or artifact, as the electrodes are moved away from the source of signal. Catheterization is, however, an invasive procedure, which involves risk.

A procedure with much less risk involves an esophageal approach. It requires placement of a small, flexible tube lowered through the nose or mouth to the region of the esophagus behind the upper portion of the heart. Electrodes at the tip of the tube, often called a catheter, obtain the signals of interest.

Whether arriving by esophagus or blood vessel, electrodes placed near the SA node obtain signals from other places too. Electric activity in the left ventricle, for example, can contribute or interfere. The left ventricle is farther from the electrodes, but it has more cells than the SA node. The relatively small voltages presented by the SA node during its repolarization, for example, may be lost in the voltages caused by depolarization of the left ventricle. Using smaller electrodes and moving them closer to each other and placing them in the node reduces interference. Repeated reduction in the size and spacing of the electrodes leads back to measurement of the action potential of but a single cell.

Figure 4.1 — Electrocardiographic connections to a patient in 1912.



A set of signals obtained simultaneously near certain groups of cells can offer important information about cardiac timing and conduction. One way to detect the conduction sequence is to use a catheter that has a series of independent electrodes encircling it. The electrodes, spaced along the length inserted into or behind the heart can obtain a set of cardiac signals that pertain to the progression of depolarization, from the SA node to the ventricular fibers. Whether the signals are worth the risk in obtaining them is an important medical question.

4.2 Signals Obtained on the Skin

Surface electrocardiography refers to a noninvasive procedure for obtaining electrocardiac information. Electrodes on the skin obtain the signals of interest. The risk is virtually nil, if the equipment is properly designed, maintained, and used. Preparation of the patient and completion of the procedure are usually easy and uneventful.

One approach to understanding how the skin offers cardiac signals involves Ohm's law. The resistance is that of the tissues in the body. The current is the movement of charges during cardiac depolarization and repolarization. A voltage results between any two points in or on the volume conductor known as the body. The voltage varies because the current, and to much less extent the resistance, varies.

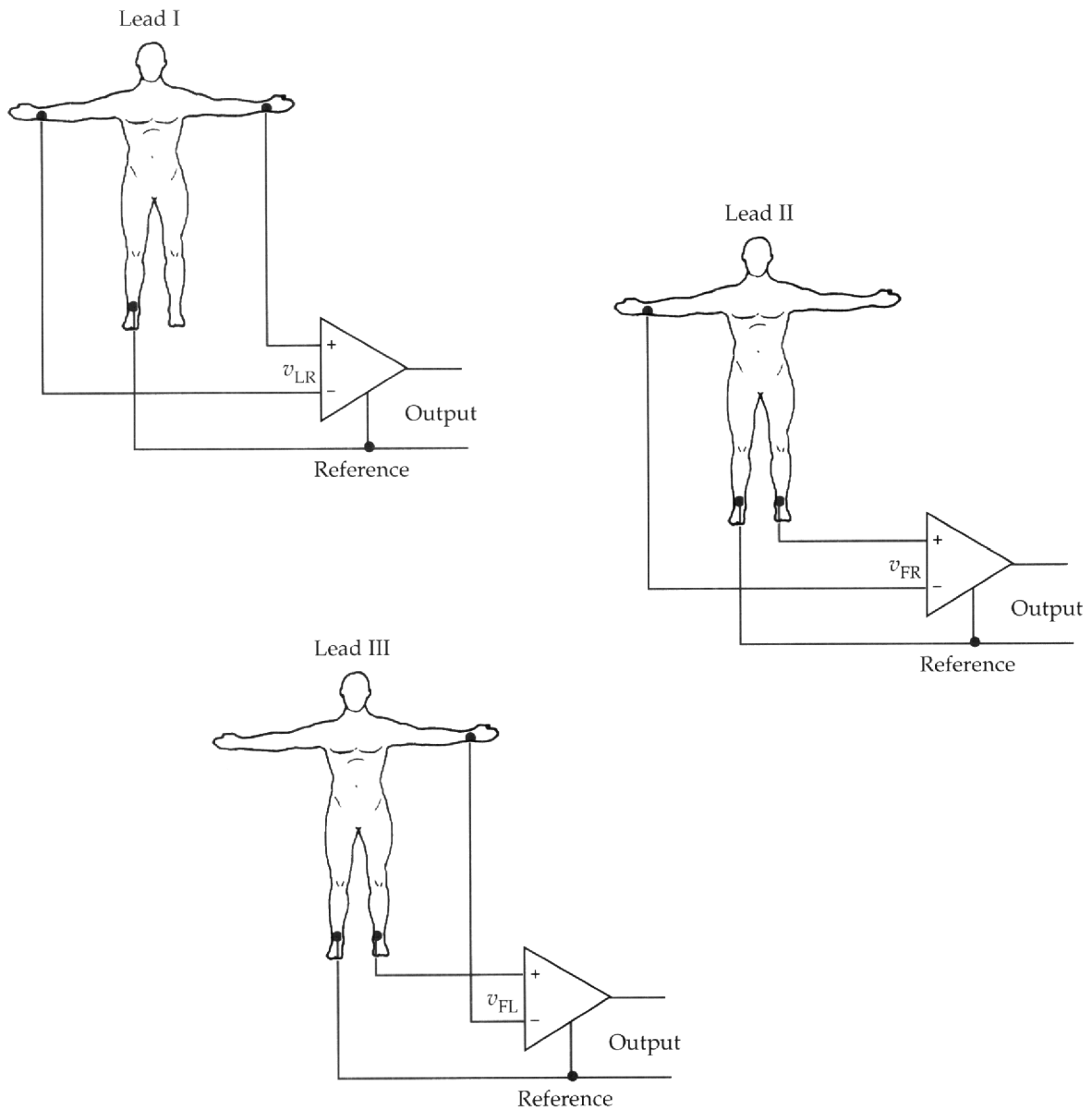
Another approach to explaining the presence of heart signals on the skin involves the electric field theory. The charges cause a field and the field creates a voltage. When the charges move, the field changes; therefore, the voltage changes. Some modifications of the field occur because the medium changes, that is, certain characteristics of the tissues vary during a heartbeat. The tissues do not constitute an unchanging, isotropic, and homogeneous medium, although most first-approximation models are based on that assumption.

The first approach, following basic circuit theory, is the choice here because it is presentable without special mathematics. In the second approach, vector calculus is necessary to explain the situation concisely.¹

4.2.1 Leads I, II, and III

Early researchers chose the hands and feet as sites for electrodes to obtain electrocardiographic signals. Another historical decision was that the voltage of the right foot should be the reference, with the other three locations providing signals for study. Figure 4.1 shows how each extrem-

Figure 4.2 — Connections for leads I, II, and III.



ity was connected to wires leading to an electrocardiograph. Buckets of salt water were the electrodes, which accommodated the subject's hands and feet.

Subsequent research showed that metal electrodes placed near the wrists and ankles obtained signals approximating those obtained from immersed hands and feet. The pertinent signals are: lead I, the signal between the left and right hands (arms); lead II, the signal between the left

foot (leg) and right hand (arm); and lead III, the signal between the left foot (leg) and the left hand (arm). Figure 4.2 presents all three circuits. The following equations show the relationships mathematically, with each lower-case, italicized v representing the instantaneous voltage and each subscript denoting an anatomic location: R for the right arm, L for the left arm, and F for the left foot. Each voltage in the array has but a single subscript, meaning that the reference for the voltage is at an infinitely remote point. The term potential, or absolute potential, is therefore common for those voltages. Although the right leg can hardly qualify as an infinitely remote point, it is the usual site of the reference electrode. The absolute potential of the right-leg electrode is not necessarily zero or static.

These equations define the first three leads:

$$\text{Lead I} = (v_L - v_R) \quad \text{Equation 4.1}$$

$$\text{Lead II} = (v_F - v_R) \quad \text{Equation 4.2}$$

$$\text{Lead III} = (v_F - v_L) \quad \text{Equation 4.3}$$

where

v_L = voltage between left arm and right leg

v_R = voltage between right arm and right leg

v_F = voltage between left leg and right leg.

Algebraically adding leads I and III produces lead II:

$$\begin{aligned} \text{Lead I} + \text{Lead III} &= (v_L - v_R) + (v_F - v_L) \\ &= (v_F - v_R) \end{aligned} \quad \text{Equation 4.4}$$

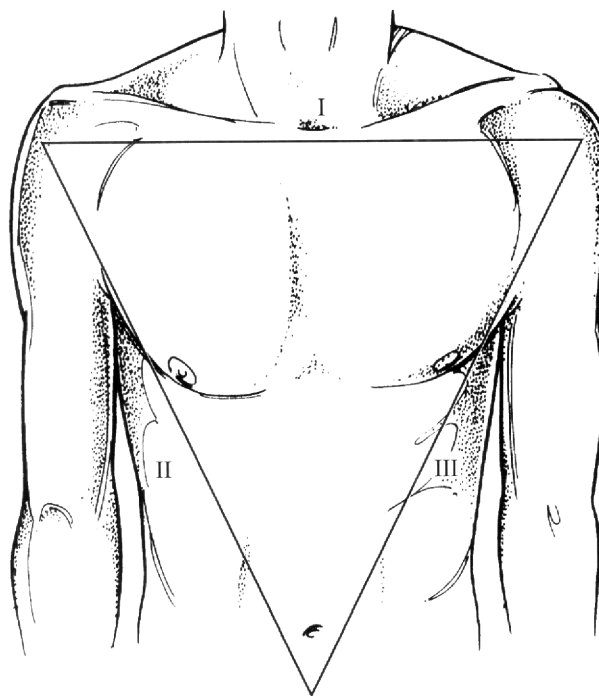
$$\text{Lead I} + \text{Lead III} = \text{Lead II.} \quad \text{Equation 4.5}$$

Equation 4.5 is a statement of Einthoven's law. The voltages are those at the sides of an equilateral triangle proposed by Willem Einthoven (Figure 4.3). Students of regular analysis of electric circuits may prefer to arrive at the same equation by applying Kirchhoff's voltage law while observing the polarities set by Einthoven for the leads. The equation, in whatever correct form, shows that any of the three leads can be determined from the other two.

A common mistake in identifying a lead is to neglect the algebraic sign. Lead II, for example, is the voltage between the left leg and right arm, v_{FR} . The voltage between the right arm and left leg, v_{RF} , is therefore $-v_{FR}$. Reversing the subscripts changes the sign of the signal. The amplifier for

Figure 4.3 — Einthoven's triangle: (a) original, equilateral. (b) modified, extended, and scalene.

(a)



(b)

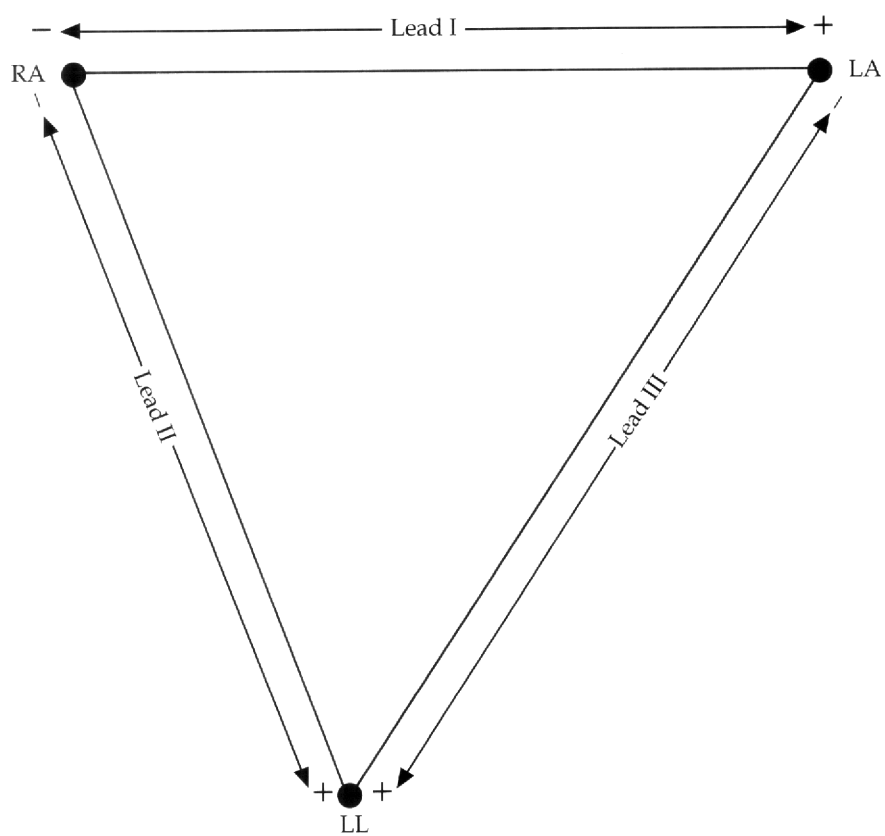
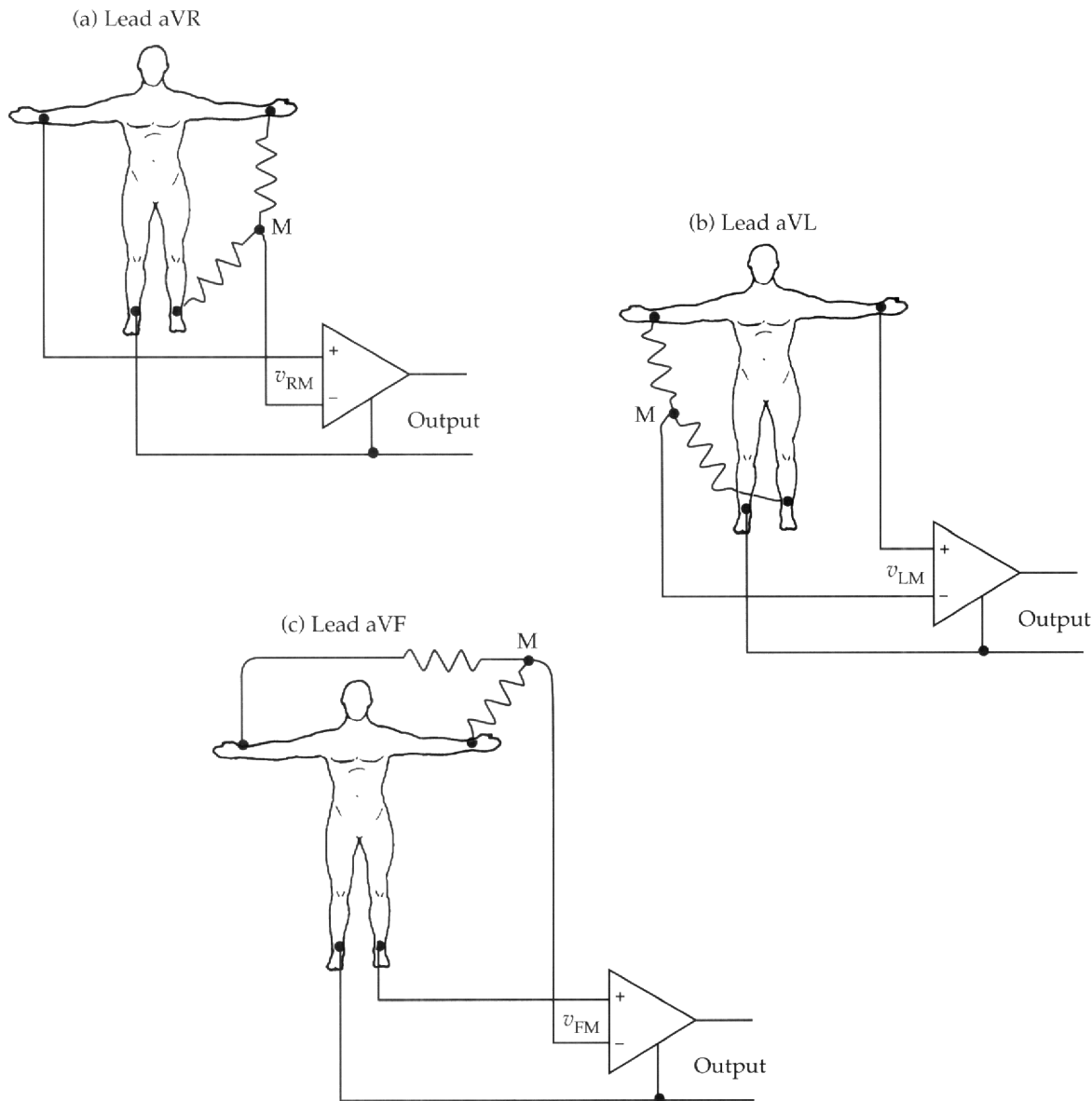
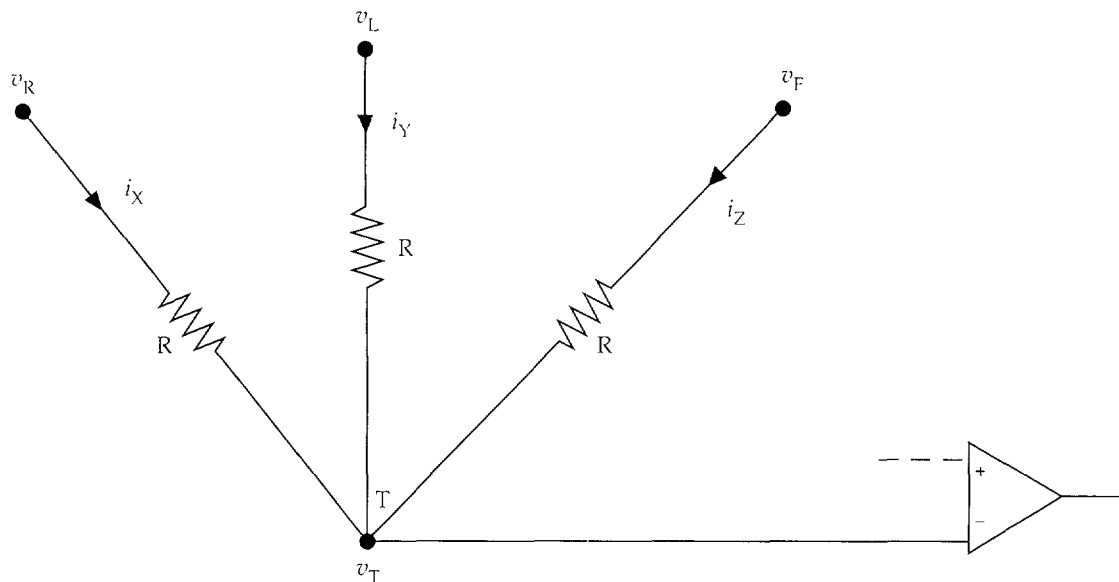


Figure 4.4 — Connections for augmented leads: (a) aVR. (b) aVL. (c) aVF.



lead II not only increases the strength of v_{RF} , it changes the sign of that voltage. That amplifier thus delivers lead II, in the original assignment of polarity, to the display system. Keeping the sign convention and the amplifier connections in mind when studying electrocardiography is very important, particularly in following an “explanation” of the relation between the movement of a depolarization wave and the inscription of the pertinent electrocardiographic deflection.

Figure 4.5 — Wilson central terminal.



An analogy for the reference points illustrates the electric relations among electrodes used for an electrocardiographic lead. In the analogy, three separate ships rise and fall with ocean swells. A sailor on ship A has the task of graphing the changing vertical distance between the prow of ship B and that of ship C. He must estimate the distance between a point on A and the prow of B and, instantaneously, he must estimate the distance between that point on A and the prow of C. Subtraction provides the vertical distance between the prows at the instant of estimation. Each repetition of the process provides a point on the plot of distance versus time. In estimating, the sailor uses point A as the reference, which is moving too. Like the point on ship A, the electrode at any reference site on or in the body undergoes changes in potential energy. The reference is useful, however, in determining the difference in potential of two other electrodes. The difference amplifier accepts each of the two signals with respect to the voltage at the reference, subtracts the signals appropriately, and amplifies the difference between the two signals.

Electronic amplification of leads I, II, and III is usually 1000. The normal time-base is 25 millimeters per second. Many electrocardiographs provide for selection of other gains, typically 500 and 2000, and an alternate time-base of 50 millimeters per second.

4.2.2 Leads aVR, aVL, and aVF

Augmented leads aVR, aVL, and aVF are usually the next three traces in the twelve-lead electrocardiogram. Figure 4.4 shows the proper connections. Each of the augmented leads depends on a modification of the point called the Wilson central terminal (Figure 4.5).² Goldberger found that removing the connection between the Wilson central terminal and the anatomic point providing the signal of interest allowed the voltage to increase.³ Each of the three leads, so augmented, gained acceptance. The right leg provides the reference. Potential v_T at the Wilson central terminal is one-third the sum of v_R , v_L , and v_F , if the resistances are equal and the connection to the negative input of the amplifier requires no current (Figure 4.6). Here is the proof, which involves the application of Kirchhoff's current law to the circuit in Figure 4.5:

$$0 = i_X + i_Y + i_Z \quad \text{Equation 4.6}$$

where i_X = current from right arm to terminal T
 i_Y = current from left arm to terminal T
 i_Z = current from left foot to terminal T.

Substitution of the appropriate v/R for each i provides, by Ohm's law:

$$0 = [(v_R - v_T)/R] + [(v_L - v_T)/R] + [(v_F - v_T)/R] \quad \text{Equation 4.7}$$

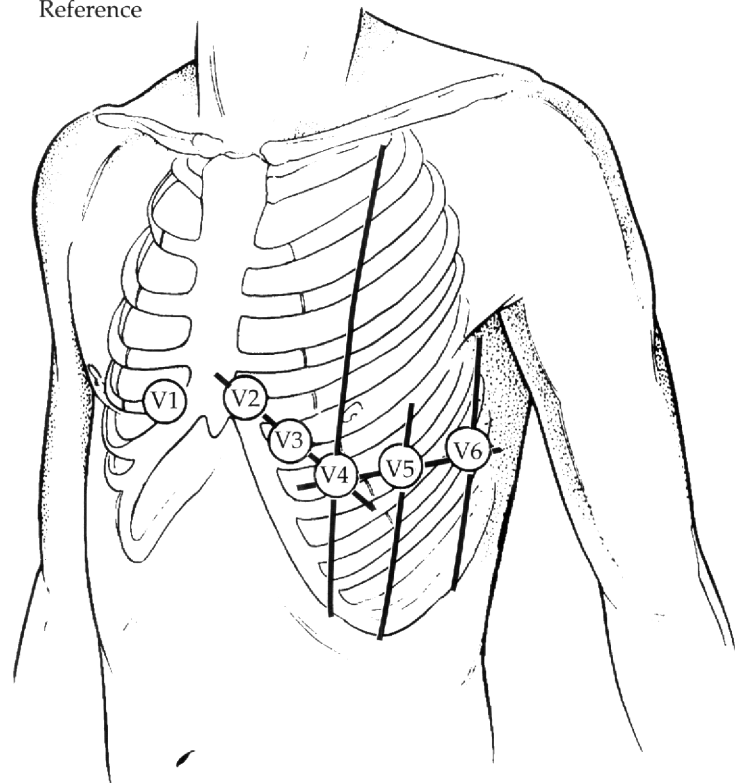
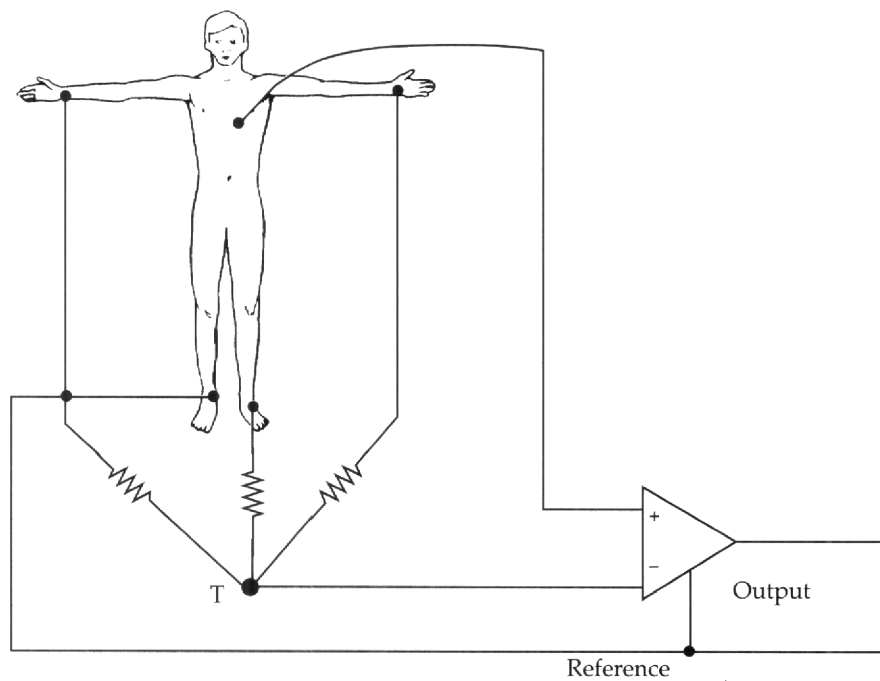
where v_R = voltage between right arm and right leg
 v_T = voltage between terminal T and right leg
 v_L = voltage between left arm and right leg
 v_F = voltage between left leg and right leg
 R = an arbitrary resistance.

Algebraic manipulation of Equation 4.7 renders:

$$v_T = (1/3)(v_R + v_L + v_F) \quad \text{Equation 4.8}$$

The modified central terminal provides potential v_M , which is one-half the sum of the two applied potentials if the resistances are equal and the amplifier requires no current. Neither v_T nor v_M is necessarily

Figure 4.6 — Connections for leads V1 through V6.



- V1 —At fourth intercostal space,
at right margin of sternum
- V2 —At fourth intercostal space,
at left margin of sternum
- V3 —Midway between sites of V2 and V4
- V4 —At fifth intercostal space,
at midclavicular line
- V5 —At same level as site of V4,
at anterior axillary line
- V6 —At same level as site of V4,
at midaxillary line

zero or static when the other potentials associated with the network are from a living person.

The term unipolar, often used in referring to an augmented lead, unfortunately suggests that the signal is of one polarity. A unipolar lead may have excursions, however, both above and below the baseline. Application of the term to the augmented leads seems to have started after consideration of the exploring electrode as one that obtains a potential in comparison with the presumed zero potential at the specified terminal. The augmented leads derive from the same anatomic locations as leads I, II, and III (Figure 4.4).

4.2.3 Leads V1 Through V6

Leads V1 through V6 are from specific locations on the chest (Figure 4.6). Sometimes called precordial or chest leads, V1 through V6 are unipolar, with the exploring electrode connected to the positive input of the amplifier, and the Wilson central terminal connected to the negative input. The right leg provides the reference. At the chest wall the electric field is strong because the generative charges are near. The potential at a site can therefore be considerably different from that at a neighboring site. Wilson, et al., in proposing that the leads be substitutes for those that would come from electrodes theoretically placed on the surface of the heart, considered the chest leads valuable in obtaining electric information from "that part of the ventricular surface which is nearest the precordial electrodes."^{4,5}

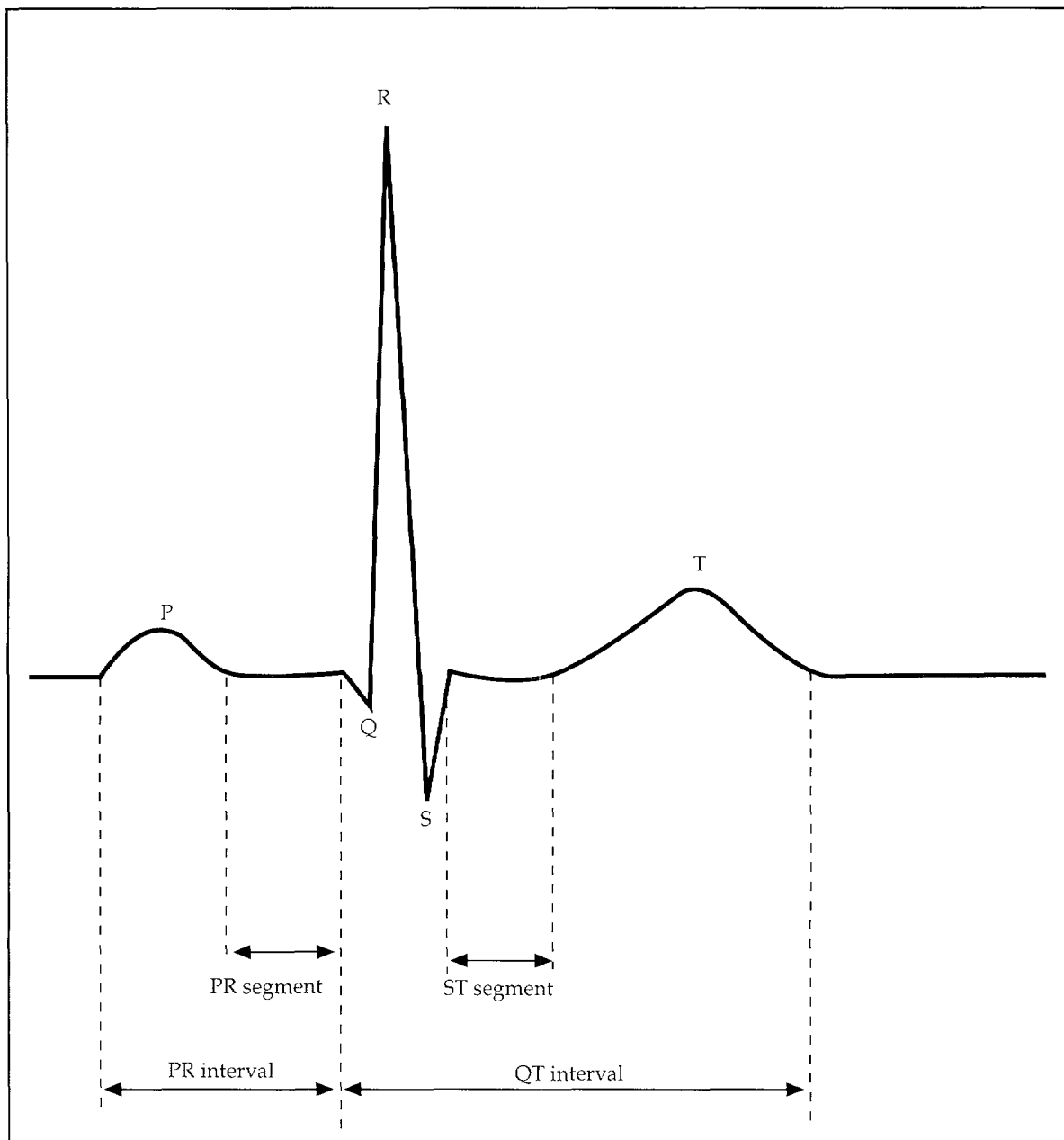
4.2.4 Normal Waves and Durations

Figure 4.7 shows a typical lead II. Each standard wave, P, Q, R, S, and T, is usually recognizable in lead II. Einthoven assigned those letters to the waves in keeping with his training in mathematics.⁶ Although the letters do not have physiologic significance, the corresponding waves do.

4.2.4.1 P Wave

Figure 4.8 relates parts of lead II to electric events in the heart. Just before the P wave, the trace is flat, which means that the voltage between the left leg and right arm is steady. Deli, Shulam, and Yongan recently affirmed that depolarizations in the SA node occur during the time sometimes called pre-P.⁷ The flatness of the trace just before the P wave does not mean electric inactivity.

Figure 4.7 — Lead II, with nomenclature.



The P wave itself occurs as the atria are depolarizing. Normal P waves have various shapes, from flat to sharply peaked, with amplitudes of 0 to 0.3 millivolts. The range of normal duration is 0 (no visible P wave) to 100 milliseconds.

Even from an individual, P waves vary in size, shape, and duration.⁸ Among the speculations for the differences are: 1) pacing may be initiated at any of several locations within the SA node, slightly altering the

delivery points of depolarization to the atrial paths; and 2) atrial depolarization may spread differently from the same site in the SA node. Boineau, et al., have challenged the idea that pacing proceeds from just one focus in the node. They urge that "atrial electrogenesis needs to be understood as a system of interacting, competing, and coordinated atrial pacemakers, widely distributed throughout the right atrium, that may include the left atrial sites as well."⁹

4.2.4.2 PR Interval

Extending from the beginning of the P wave to the first component of the QRS complex, the PR interval relates to the depolarization of the atria, AV node, AV bundle and its branches, and the Purkinje system (Figure 4.7). The PR interval starts as depolarization begins in the atria and stops when depolarization begins in the ventricles (Figure 4.8). If a Q wave is absent, the PR interval extends to the R wave, a specification that seems to account for the name of the interval. The normal range of the interval is 120 to 200 milliseconds.

Age and heart rate are important natural influences on the PR interval. In people over the age of 65, the interval may be 210 milliseconds, for example, without causing great concern that the prolongation means first-degree heart block. Sinus tachycardia can reduce the interval to about 110 milliseconds.

4.2.4.3 Q Wave

A normal Q wave may be an absent one: the range of amplitudes considered normal is 0 to 25% of the amplitude of the associated R wave. The duration of a Q wave is normally less than 30 milliseconds.

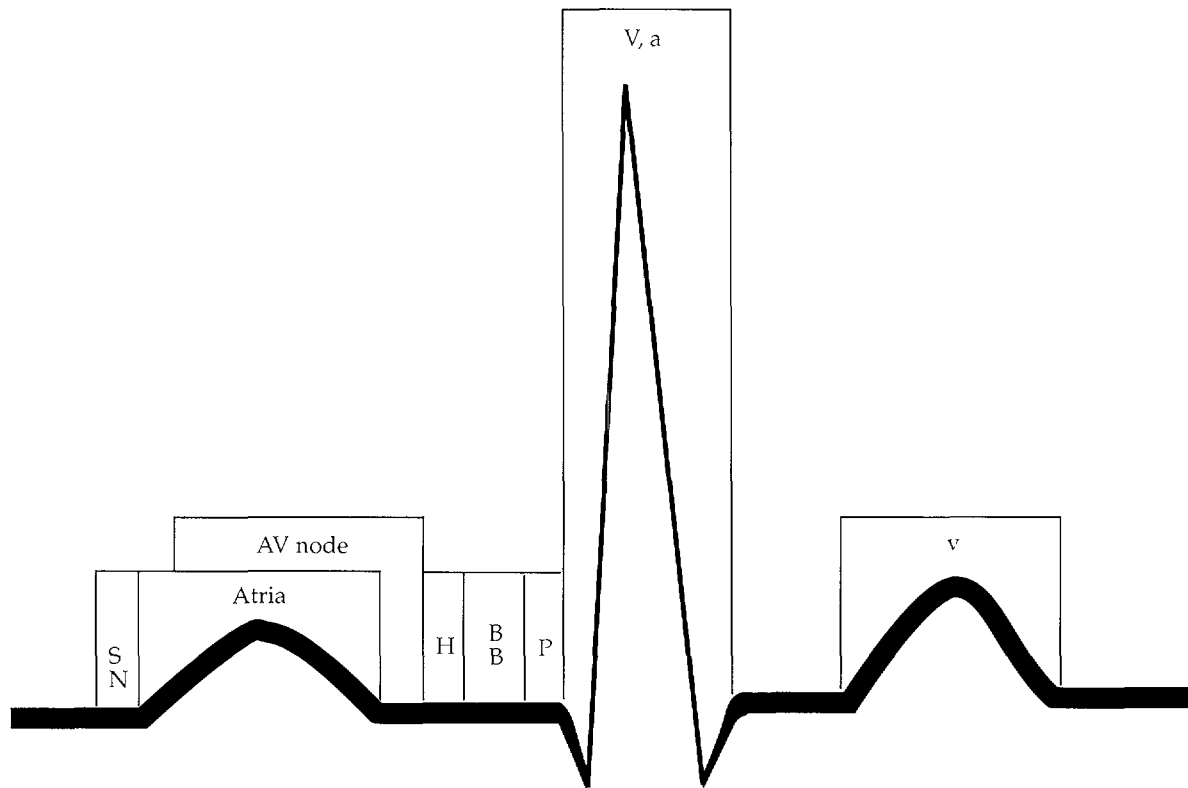
4.2.4.4 R Wave

The amplitude of an R wave may be as low as 0.05 millivolt or as high as 2.8 millivolts and still be considered normal. The duration of an R wave is usually less than 70 milliseconds.

4.2.4.5 S Wave

A normal S wave has an amplitude of 0 to 0.8 millivolt and a duration of 0 to 50 milliseconds.

Figure 4.8 — Lead II, with notations of electrocardiac activity.



Depolarization in:

SN	Sinoatrial node
Atria	Right atrium and left atrium
AV node	Atrioventricular node
H	Bundle of His
BB	Bundle branches
P	Purkinje network
V	Right ventricle and left ventricle

Repolarization:

a	Right atrium and left atrium
v	Right ventricle and left ventricle

4.2.4.6 QRS Complex

As an electrocardiograph records the QRS complex, the heart is undergoing ventricular depolarization and atrial repolarization. Because of the large number of ventricular cells and small number of atrial cells participating in electric events, ionic movements abound. The electric field and the isopotential contours change accordingly. The voltage between the left leg and right arm therefore changes, and the record acquires the QRS complex. The duration of a normal QRS complex in lead II is 50 to 100 milliseconds.

One convention for naming the components of the QRS complex is:

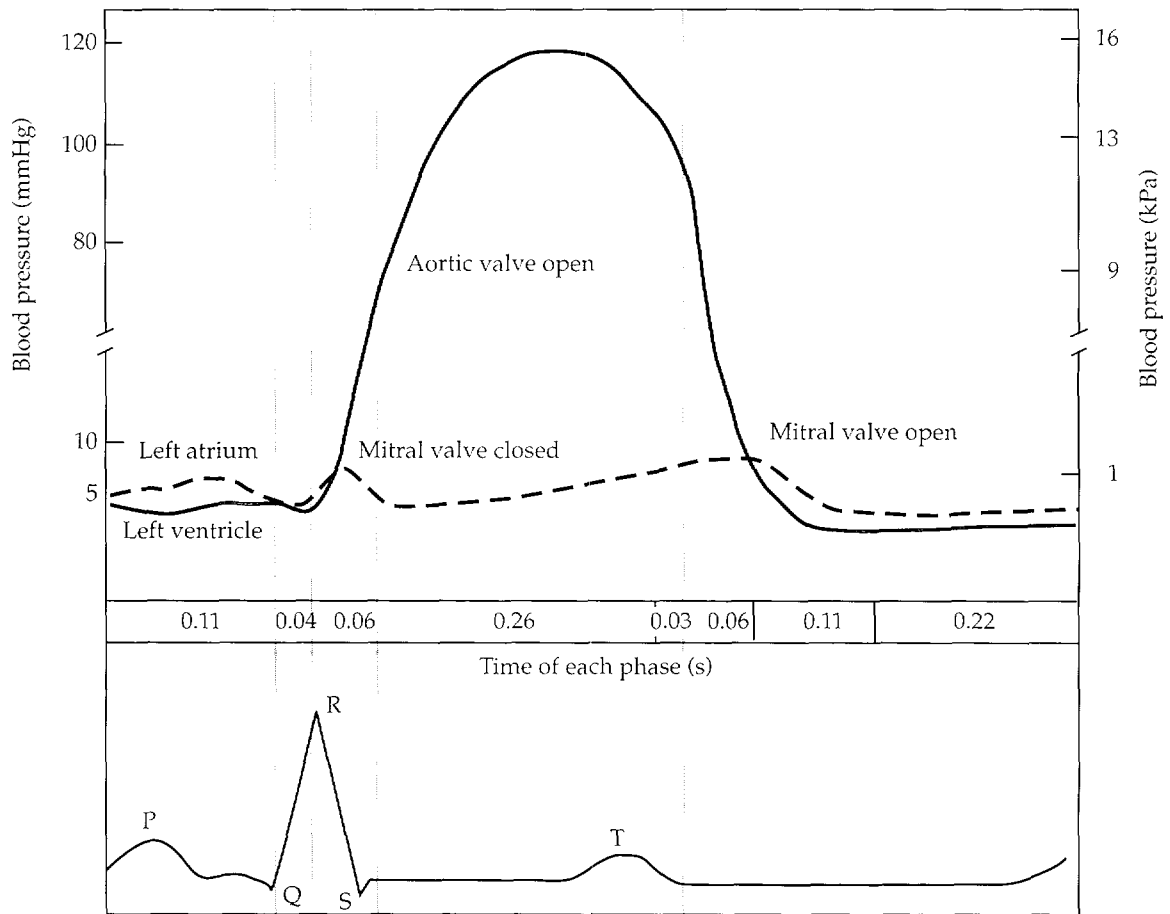
- Q wave - the first downward deflection
- R wave - the first upward deflection
- S wave - the first downward deflection following the R wave
- R' wave - the second upward deflection
- S' wave - the first downward deflection following the R' wave
- QS complex - the single, negative deflection representing the entire QRS complex (upward deflection absent).

In the convention, upper-case letters signify large amplitudes while lower-case letters signify small amplitudes. The absence of a letter signifies the absence of the wave. A QR complex is thus one that has a small Q wave, a large R wave, and no S wave.

4.2.4.7 ST Segment

The ST segment extends from the end of the QRS complex to the beginning of the T wave (Figure 4.7), and it is normally flat or just slightly inclined or elevated. Deviations refer to the baseline established by the PR segment, which connects the end of the P wave to the beginning of the QRS complex. The American Heart Association recommends the use of the PR segment as the baseline, but another conventional baseline is the TP interval preceding or following the ST segment under measurement. A normal inclination or elevation of the ST segment is 0 to 0.2 millivolt, which is 0 to 2 millimeters of deflection if the scale is the usual 10 millimeters per millivolt. A normal declination or depression is 0 to 0.05 millivolts, or 0 to 0.5 millimeters on the usual scale. In describing such inclinations and declinations, some electrocardiographers mention the J-

Figure 4.9 — Lead II related to left-atrial and left-ventricular pressures.



point, the junction of the end of the QRS complex and the beginning of the ST segment. Individuals with the “normal variant” called early repolarization produce a J-point that is slightly below an elevated ST segment.

4.2.4.8 QT Interval

Measured from the beginning of the QRS complex to the end of the T wave, the QT interval relates to the duration of the depolarization and repolarization of the ventricles (Figure 4.7). The interval varies with heart rate, age, and sex of the patient. Among the pertinent formulas and tables in the literature is a very simple formula offered by Grauer and Curry.¹⁰ Their formula, to divide the R-R interval by 2, renders an upper limit for the QT interval. Another method, presented by Bazett in 1918,

is to determine a calculated QT interval by dividing the measured QT interval by the square root of the R-R interval.¹¹ The calculated interval should be shorter than 425 milliseconds. A table, such as the one offered by Friedman, is yet another way to obtain the information.¹²

4.2.4.9 T Wave

The T wave occurs during ventricular repolarization. Tables of electrocardiographic measurements show various ranges for the amplitude of normal T waves; one such range is 0 to 0.8 millivolt. The duration of a normal T wave is 100 to 250 milliseconds. A healthy person might produce inverted T waves by hyperventilating or by ingesting hot or cold food or drink shortly before being connected to the electrocardiograph.

4.2.4.10 U Wave

The U wave is a little deflection that is visible just after the T wave in a few electrocardiograms. It has the general shape of the T wave and 5 to 25% of its amplitude. One theory about the cause of the U wave is that it relates to the final phase of ventricular repolarization. Another theory proposes that the U wave is caused by afterpotentials at the beginning of diastole.

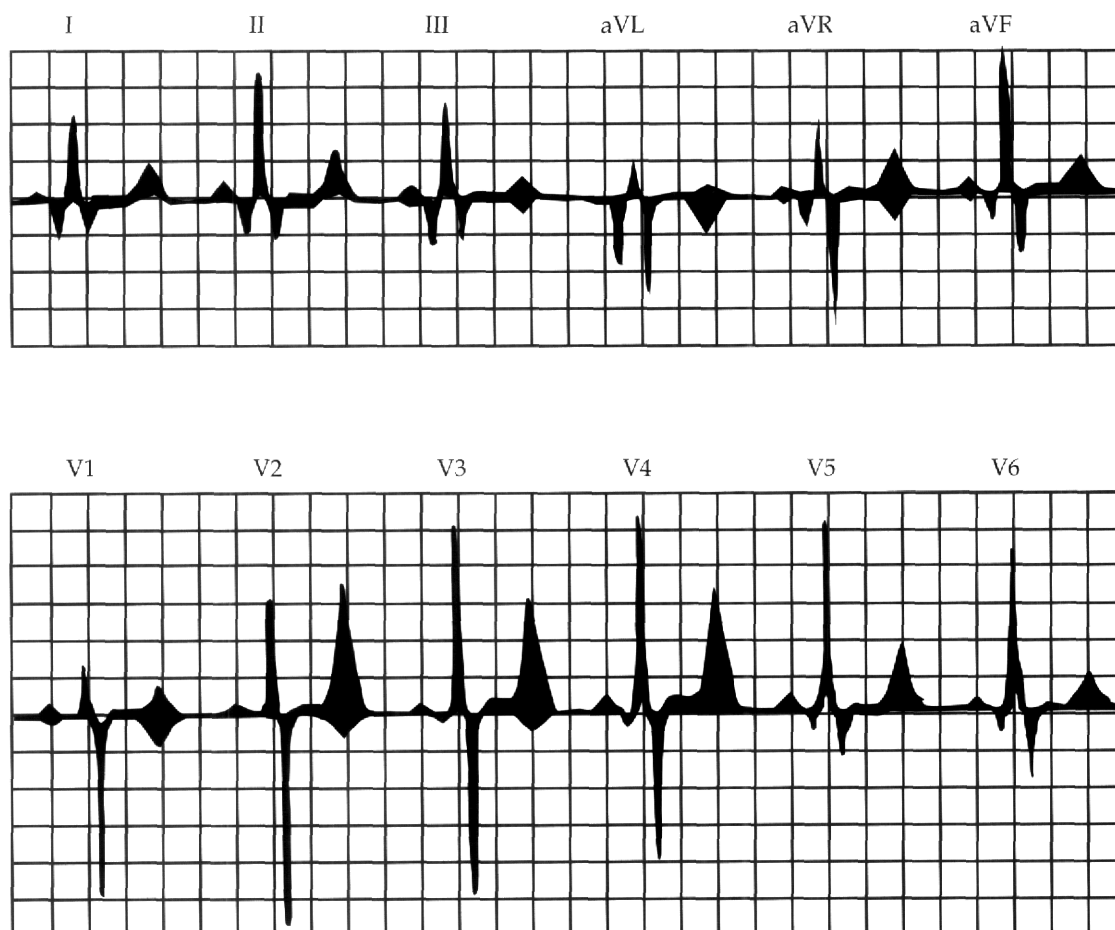
4.2.5 Relation Between Excitation and Contraction

Figure 4.9 shows that the increase in atrial pressure relates to the P wave and that the increase in ventricular pressure relates to the QRS complex. Contraction normally follows excitation of the chambers of the heart. The practice of equating the rate of P waves to the rate of atrial contraction and the rate of R waves to the rate of ventricular contraction is, therefore, usually appropriate.

4.2.6 Imprecise Measurements

All the amplitudes and durations presented above relate to lead II. In other leads, the waves can have—and in some leads should have—different shapes and durations. Figure 4.10 shows the variations among the leads and the range of normal values for each wave of each lead. The variations among the leads are reasonable because of the different anatomic locations from which the signals are obtained. The ranges of nor-

Figure 4.10 — Twelve-lead electrocardiogram, showing normal ranges of each wave in each lead.



mal values of each wave of each lead reflect the electric diversity in the bodies of people with healthy hearts. Differences in the size, shape, position, and movement of hearts account for some of the differences in shapes and durations in electrocardiographic waves.

Much of the imprecision in measurement of important intervals and segments results from the inability to locate one, and sometimes both, of the boundaries exactly. In some leads, the beginning and end of a T wave, for example, are indistinct; measurements of the related ST segment and QT interval are, therefore, imprecise.

4.3 ***Reminder Regarding Sources of Electrocardiac Signals***

Electric activity in the heart takes place in three dimensions; moreover, the heart undergoes changes in size, shape, and orientation as it beats. Surrounding the heart is a membranous sac, called the pericardium, which is normally separated from the heart by a very thin layer of fluid. Beyond the pericardium is a variety of tissues and, in some directions, the gases contained in the lungs. A crude model of the system just described is a somewhat conductive, plastic bag in human form, almost filled with sea water in which an electronic generator moves through an odd, three-dimensional pattern as it produces current.

The heart is just one of the masses of cells undergoing ionic movement during a cardiac cycle. Ionic movement occurs as well in nerves, skeletal muscles, and so on. Signals on the skin and those obtained inside the body result from all the electric events in the internal environment and, indeed, from sources in the external environment. Electromyographic signals often interfere with electrocardiographic signals, causing noise, or artifact, in the record. Another common source of artifact is a power line: voltage at line frequency (60 hertz in the United States) sometimes embroiders the otherwise thin line of an electrocardiogram.

5.0 **NONTRADITIONAL ELECTROCARDIOGRAPHIC VOLTAGES**

5.1 ***Body-Surface Potential Maps***

Electrocardiac signals exist everywhere in and on the body of a living person. The signals can be different at different locations. Leads V1 through V6, for example, demonstrate that differences occur even at neighboring locations on the skin. Any two locations on the skin can provide a lead, although only a few pairs have gained importance in clinical, surface electrocardiography.

Each of the 12 leads of traditional electrocardiography offers a continuous series of undulations in voltage measured with respect to time. The leads are temporal signals, yet they afford a somewhat spatial concept because the electrodes are at various locations on the body. A common metaphor is that each lead provides a different electric view of the

In fundamental electrostatics the concentric array of equipotential lines for a single charge in otherwise empty space (Figure 1.1) and the map of contours for two unlike charges—a dipole—in otherwise empty

space (Figure 1.2) are easy to imagine and sketch. In contrast, a map of equipotential contours for the surface of the human heart is difficult to develop without actual measurement. Unlike the static dipole of the fundamental illustration, the heart is, electrically, a confinement of many moving dipoles. Another important dissimilarity is the medium in which the charges exist: a perfect vacuum in the fundamental illustration and an imperfect mass of nonisotropic, nonhomogeneous tissues in the human. A map pertaining to the ideal dipole has smooth contours. Most BSPMs have distorted contours, and some have several maxima and minima of potential.

Equipotential maps can have four dimensions: length, width, depth, and time. A three-dimensional model in which the equipotential surfaces change continuously could illustrate the system. Much of the current illustration, however, involves only two-dimensional, or planar, maps (Figure 5.1).

Accurate determination of each contour in a map requires an infinite number of electrodes, and each electrode must be infinitesimally small. Practicality prevails, so that sometimes even fewer than fifty measurements on the chest and back suffice. If too many electrodes are connected to the skin, distortion of the pattern of equipotentials can result. If too few electrodes are connected, some details do not appear in the contours. The signal obtained by each electrode needs amplification and processing, so complications and costs increase, however nonlinearly, with the number of electrodes.

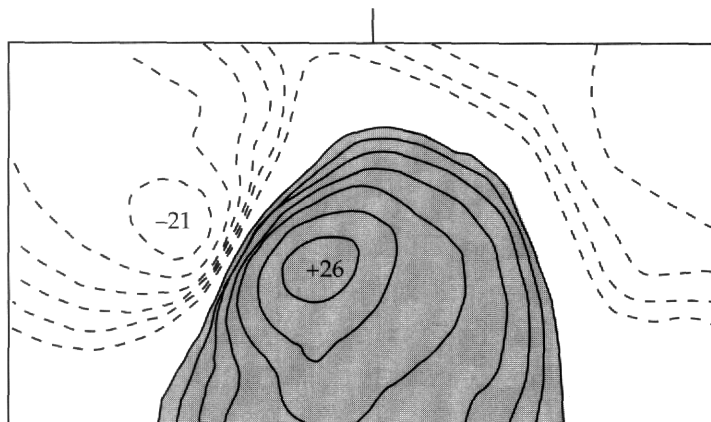
A second kind of map involves contours of time-integrals of the potentials. Each contour shows the chain of locations at which the potential, integrated for a selected time, such as the QRS duration or a fraction of it, is the same. The usual unit for each value is a microvolt-second (Figure 5.2).

A third kind of map depicts the difference between the potential at each point and the potential that is the average for that point on a healthy person. The resultant pattern is a departure from the average map. Another name for the departure pattern is the deviation index map (Figure 5.3).

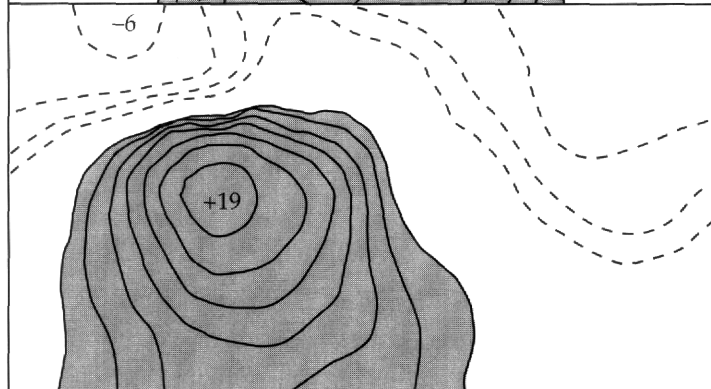
Some maps in the literature show time-derivatives of the potentials. Others show the locations of the same root-mean-square value of the potentials measured in a defined period, such as all or part of the QRS interval of lead II.

Figure 5.2 — Map of contours of equal time-integral of potentials.

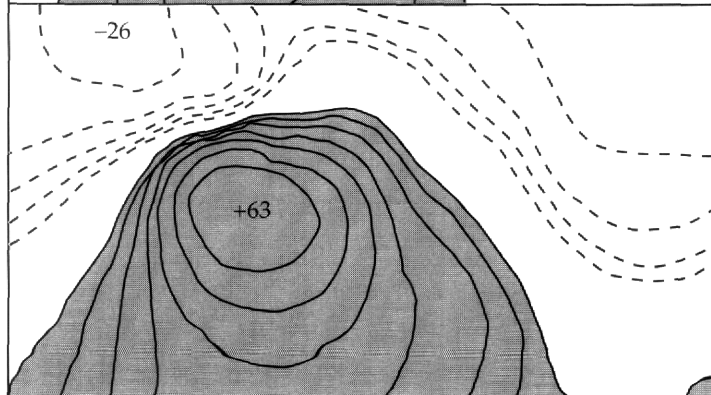
Integration during QRS complex



Integration during ST segment



Integration during T wave



Front

Back

Figure 5.3 — Departure maps with corresponding isopotential (equipotential) maps at 10-millisecond intervals after onset of normal QRS complex.

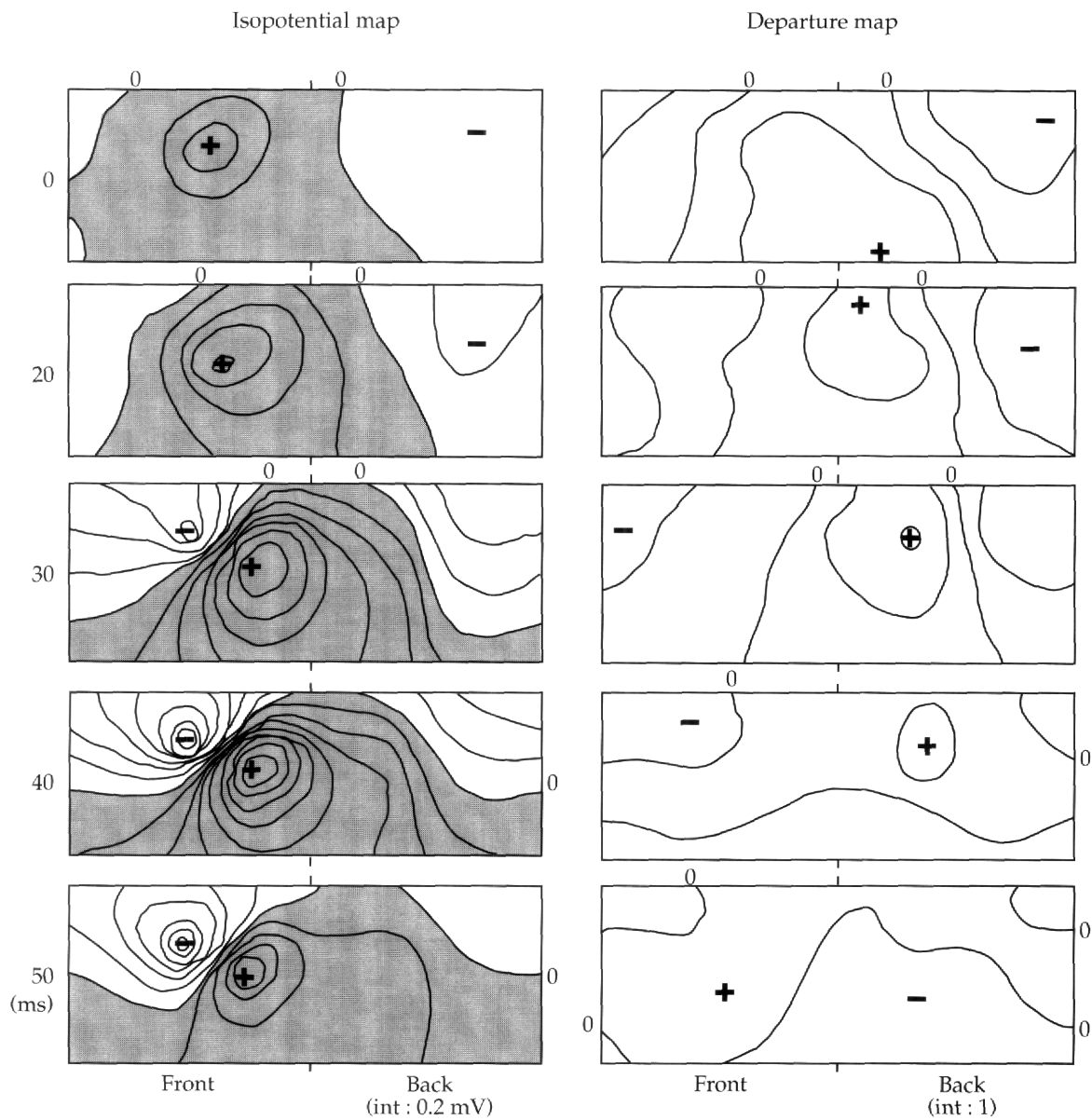
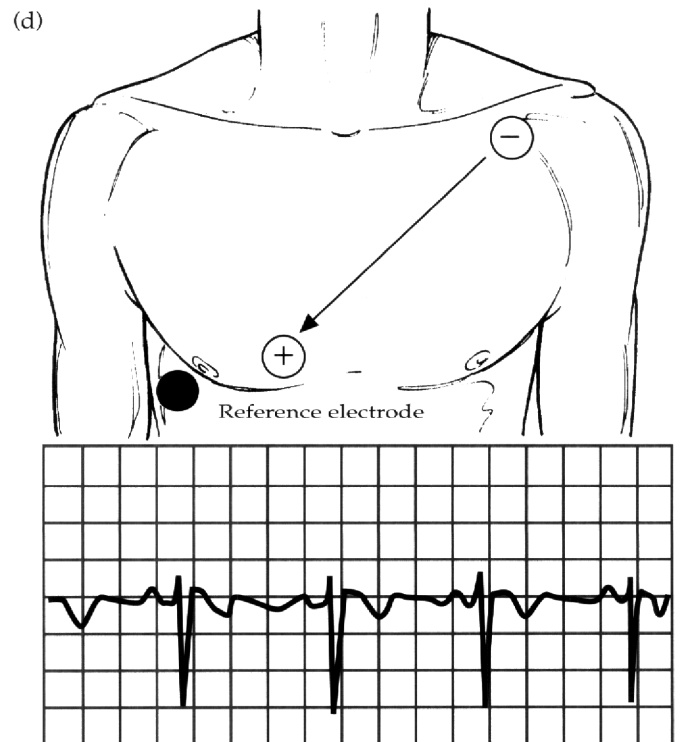
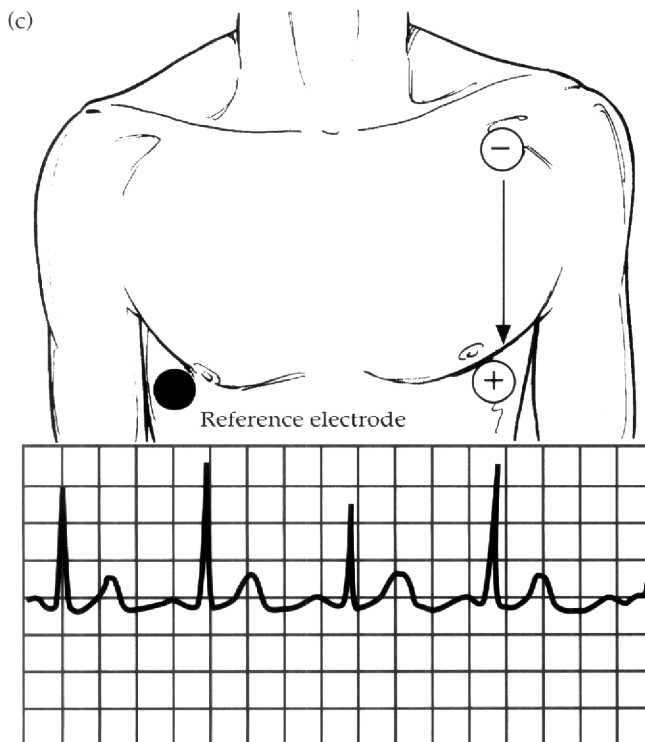
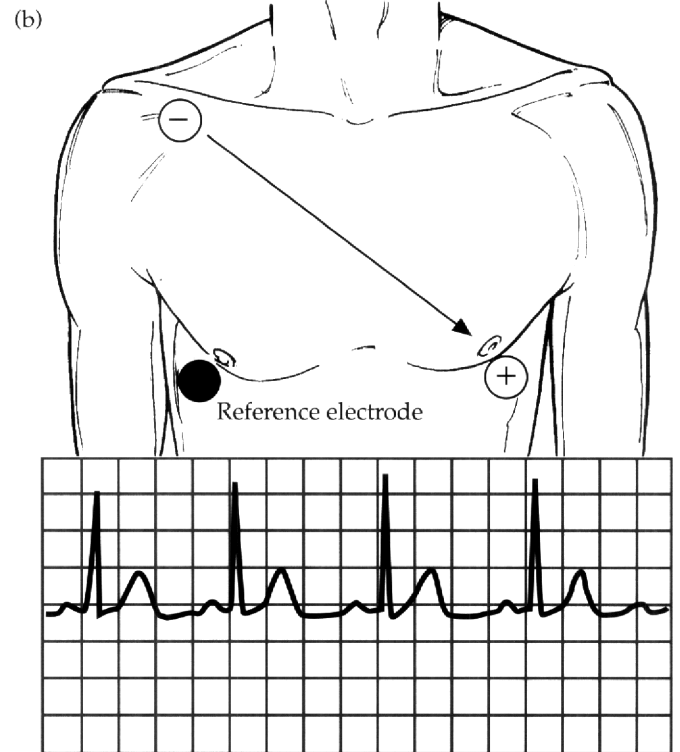
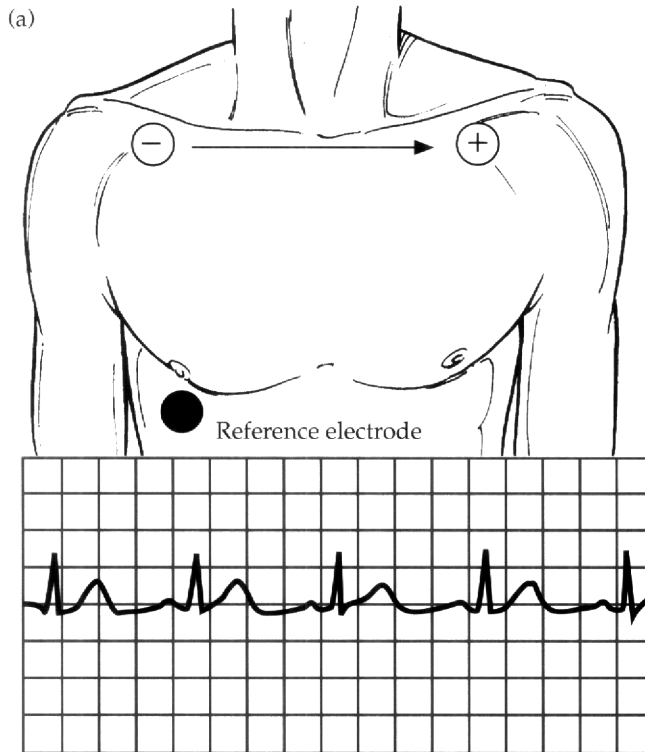


Figure 5.4 — Placements of chest electrodes: (a) For signal similar to lead I. (b) For signal similar to lead II. (c) For signal similar to lead III. (d) For lead MCL_r.



5.2 *Special Signals on the Torso*

Two separate electrodes placed anywhere on the torso can detect a signal of cardiac significance. Some of the signals have the appearance of lead II, which is preferred by many cardiologists. In lead II the P, R, and T waves are usually identifiable, and they provide atrial as well as ventricular information. Figure 5.4 (a through c) shows the sites at which signals similar to leads I, II, and III can be obtained on the chest. The connections shown in Figure 5.4d are for MCL_1 , which is a modification of the V1 chest-lead.¹³ In Figure 5.4 the reference electrode is below the right pectoral muscle, an arbitrary location. The polarities on the sites pertain to the connections at the amplifier; for example, a wire connected to an electrode at a position marked with a minus sign should go to the negative input of the amplifier.

Lead MCL_1 is considerably different from any other shown in Figure 5.4, but the atrial and ventricular components are usually distinguishable, as in certain other leads. The electrodes for MCL_1 are away from the area in which defibrillator paddles might be applied.

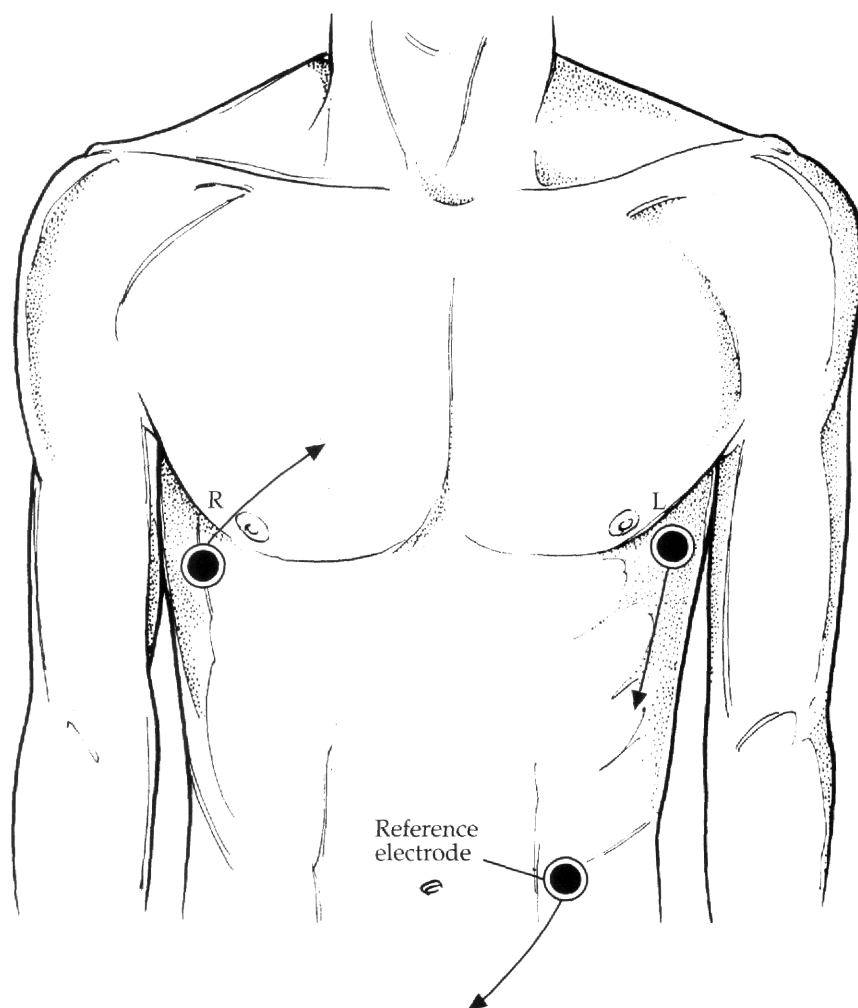
Some books and manuals give very specific anatomic descriptions of the sites at which electrodes should be placed to obtain a certain type of electrocardiographic signal from the torso. Electrodes at the specified sites, however, can obtain an unacceptable signal, so several books offer directions for relocating electrodes to get an acceptable signal. Figure 5.5 shows how one book presents information on electrode placement and relocation.

What makes a lead special is simply its utility or acceptance. Many signals qualify, even those with only local champions. Some healthcare professionals prefer a signal from a linear placement of electrodes, as in MCL_1 ; others insist on a signal from a triangular placement reminiscent of Einthoven's notation (Figure 4.3). Each signal has real or perceived advantages, making it special, by definition. A report of a task force of the American Heart Association recommends standardization of lead systems for monitoring. Another recommendation in that report is: "...future monitors should be capable of simultaneously displaying and analyzing at least two and preferably three or more leads."¹⁴

5.3 *Interdigital Signals*

The voltage between any two fingers has an electrocardiographic component. Some periodic monitoring of cardiac patients at home, espe-

Figure 5.5 — Yet another placement of chest electrodes, showing exploratory paths.



cially those with implanted pacemakers, relies on signals from fingers. The signal can come from the index finger of each hand, for example. Conversion of the analog signal to a digital one allows suitable transmission over telephone lines to a location such as a physician's office.

5.4 Toilet-Seat Signals

Because straining during defecation can provoke a cardiac arrhythmia, monitoring during what are sometimes called Valsalva maneuvers may be reasonable for some patients. Electrodes on the two sides of the toilet seat can obtain the signal, which can be evaluated by an arrhythmia detector.¹⁵

5.5 ***Esophageal Signals***

A mildly invasive way to get electrodes close to the heart is to maneuver them to an appropriate place in the esophagus. Various devices are available for this purpose, including bipolar pacing catheters and standard nasogastric tubes with an array of electrodes. A "pill electrode," which has an electrode near each end, is another device for obtaining the signals.¹⁶ The patient swallows the pill with water. The wires that lead from the pill to the amplifier hold the pill at the desired level for obtaining electrocardiac signals. One method for estimating the level of the pill is to observe relative peaks of the P and R waves while moving the pill slowly up or down the esophagus.

Figure 5.6a shows connections advocated for obtaining lead II and esophageal signals simultaneously. The preamplifier provides some isolation between the right arm and the esophageal electrodes, a gain of 2, and high-pass filtering with a "corner frequency" of 5 hertz. Figure 5.6b presents the simultaneous signals.¹⁷ In the bipolar esophageal electrocardiogram (BEE) of Figure 5.6c, the P wave of the esophageal signal increases because the pill is being moved from a low ventricular position to an atrial position.

Esophageal leads can be helpful in studies of the electric events in the atria and the correspondence of those events to the electric activity in the ventricles. Figure 5.7 shows a typical BEE and the corresponding lead II. The BEE clearly demonstrates atrial tachycardia.

5.6 ***Intracardiac Signals***

Electrodes at or near the ends of catheters eased into the heart by way of certain veins can obtain signals of diagnostic importance. The conventional name for the record of an intracardiac signal is the electrogram, which is usually preceded by an anatomic modifier. A sinus-node electrogram (SNE) is, therefore, a recording of the signal obtained by intracardiac electrodes near the SA node.¹⁸ A His-bundle electrogram (HBE) shows the signal near the His, or AV, bundle.¹⁹

Studies in cardiac electrophysiology involve various electrograms, some of which are deliberately provoked by electric stimulation delivered through pacing catheters.²⁰ Critically timed stimuli can help in determining the mechanisms of some cardiac arrhythmias and in evaluating therapy. Catheterization of the heart has particular risks, however, and so does the pacing. A recent article offers this somewhat reassuring com-

Figure 5.6 — Esophageal electrocardiography:
 (a) Connections for simultaneous lead II and bipolar
 esophageal electrocardiogram. (b) Typical normal traces.
 (c) Bipolar esophageal electrocardiogram showing
 changes in signal as location of pill is changed.

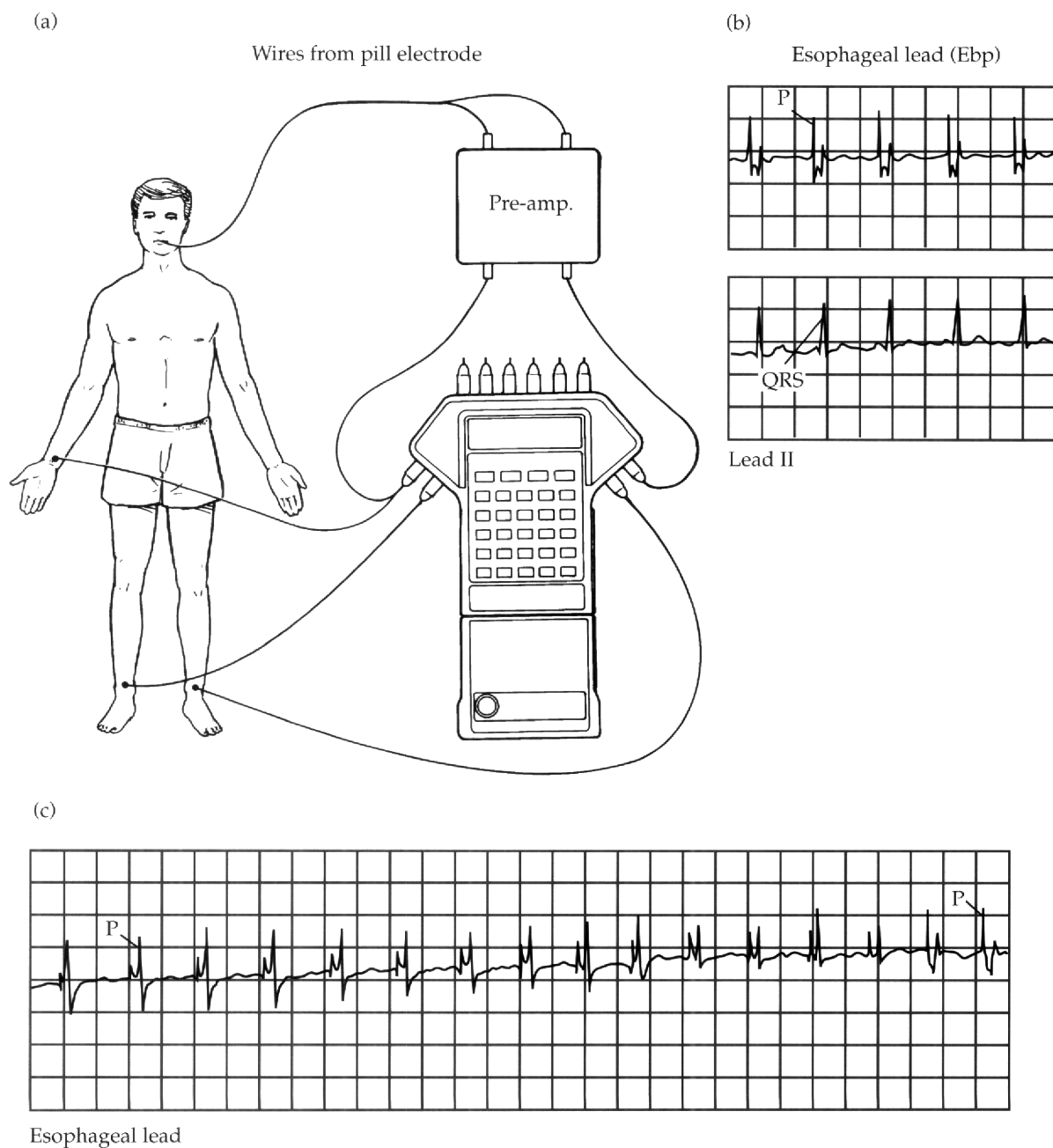
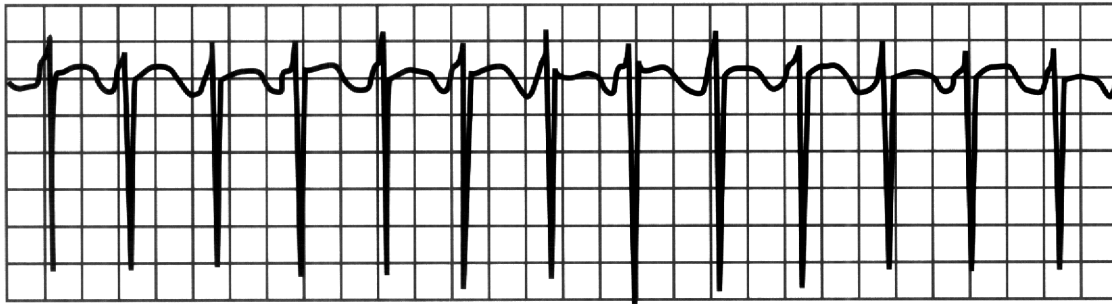


Figure 5.7 — Simultaneous bipolar esophageal and lead II electrocardiogram, from case involving atrial tachycardia.

BEE



lead II



ment on safety: "Electrophysiologic studies are safe even though they frequently induce tachycardia that necessitates cardioversion."²¹

5.7 ***Epicardial Signals***

Application of electrodes to the myocardium involves thoracic surgery, with all the attendant risks. Epicardial signals from dogs and other animals, however, provide some useful information relative to human electrocardiography. An elastic fabric in which electrodes are imbedded, called a cardiac sock, is one means of obtaining the signals. Epicardial signals from humans are useful in very specialized surgery, such as that necessary in attempting to destroy abnormal paths of conduction causing the Wolff-Parkinson-White syndrome.²²

Table 6.1 – Electrocardiographic deflections, in tenths of millivolt.

Lead	P				Q				R				S				ST				T			
	No. Cases	Min.	Max.	Mean	No. Cases	Min.	Max.	Mean	No. Cases	Min.	Max.	Mean	No. Cases	Min.	Max.	Mean	No. Cases	Min.	Max.	Mean	No. Cases	Min.	Max.	Mean
I	475	0	2.5	0.69	505	0	2.0	0.27	505	0.7	19.4	5.51	505	0	6.4	1.27	100	-0.3	0.9	0.11	505	-0.5	5.6	2.20
II	475	0	3.0	1.07	505	0	4.0	0.38	505	0.5	28.0	9.41	505	0	8.2	1.36	100	-1.0	1.0	0.21	505	0	8.0	2.67
III	475	-0.8	2.0	0.56	505	0	4.0	0.48	505	0	22.0	5.56	505	0	13.0	1.29	100	-0.6	0.8	0.04	505	-2.0	5.5	0.77
VR	32	-1.0	-0.5	-0.63	62	0	8.0	2.48	62	0	3.0	0.90	62	0	11.0	3.01	32	0	0	0	62	-4.0	-0.5	-1.65
VL	32	-0.5	0.5	0.07	62	0	1.5	0.16	62	0	7.0	1.21	62	0	7.0	2.01	32	0	0	0	62	-1.0	1.5	0.29
VF	32	0	2.0	0.72	62	0	2.0	0.30	62	0	15.0	6.82	62	0	6.5	0.74	32	0	0	0	62	0	4.6	1.40
aVR	411	-1.5	-0.01	-0.79	552	0	16.8	2.38	552	0	4.1	0.94	552	0	15.7	3.76	—	—	—	—	479	-5.5	-0.2	-2.49
aVL	411	-1.0	1.4	0.51	552	0	3.5	0.27	552	0	10.1	2.61	552	0	11.3	1.35	—	—	—	—	479	-4.0	6.0	-0.73
aVF	411	-1.8	1.7	0.74	552	0	3.0	0.38	552	0	20.0	4.73	552	0	7.1	0.81	—	—	—	—	479	-0.6	5.2	1.85
V1	371	-1.1	2.2	0.57	567	0	0	0	567	0	15.5	3.09	567	0.8	26.2	9.44	33	0	0.5	0.01	512	-4.0	12.2	0.84
V2	371	-0.7	2.0	0.60	594	0	0	0	594	0	23.0	5.96	594	0	39.2	14.09	33	0	1.0	0.09	512	-2.6	18.0	4.70
V3	371	-0.5	2.0	0.61	567	0	1.5	0.01	567	0.7	54.6	8.93	567	0	27.5	9.51	33	0	2.0	0.20	512	-2.0	21.0	5.16
V4	371	-0.2	2.3	0.60	594	0	4.0	0.13	594	1.8	46.0	13.78	594	0	28.8	5.93	33	0	1.0	0.03	512	-0.5	17.0	5.06
V5	371	0	2.4	0.56	567	0	3.4	0.43	567	0.4	33.6	12.01	567	0	16.1	1.96	33	0	0	0	512	0	11.0	3.83
V6	371	0	1.8	0.54	564	0	2.7	0.44	564	2.0	22.6	9.68	564	0	14.3	1.00	33	0	0	0	512	0	6.9	2.80
VE	—	—	—	—	30	0	0	0	30	2.0	12.8	5.81	30	0	16.2	6.09	—	—	—	—	30	0.2	5.2	2.55

6.0 CHARACTERISTICS OF ELECTROCARDIOGRAPHIC SIGNALS

6.1 Amplitudes

Table 6.1 shows the ranges of amplitudes of various waves in a normal electrocardiogram. Each entry is in tenths of a millivolt. Figure 4.10 depicts the ranges graphically, as zones for each wave. The ranges of normal values are remarkably large. A wave can even be absent, that is, it can have zero amplitude in a particular lead. That lead can nevertheless indicate a healthy condition.

Part of the difficulty in using amplitude to determine electrocardiac abnormality is that the placement of electrodes refers to a perceived requirement for uniformity. The measured system is, however, remarkably nonuniform. Neither the location nor the movement of the heart is the same among individuals. The electric characteristics of the body of an individual may not be the same as those in another individual. Comparisons of amplitudes of electrocardiographic waves are therefore more

indicative when the waves are from electrocardiograms of the same person. A reference electrocardiogram, taken when the person has no cardiac disorder, can serve as the norm for that person.

6.2 ***Frequency Content***

Fourier analysis is one of the mathematic methods in studies of electrocardiographic signals. The theory is that a physically realizable signal, such as an electrocardiac one, can be considered an algebraic sum of components. The first component is steady; all others alternate sinusoidally. In the summation, all components at various frequencies from zero to infinity contribute.

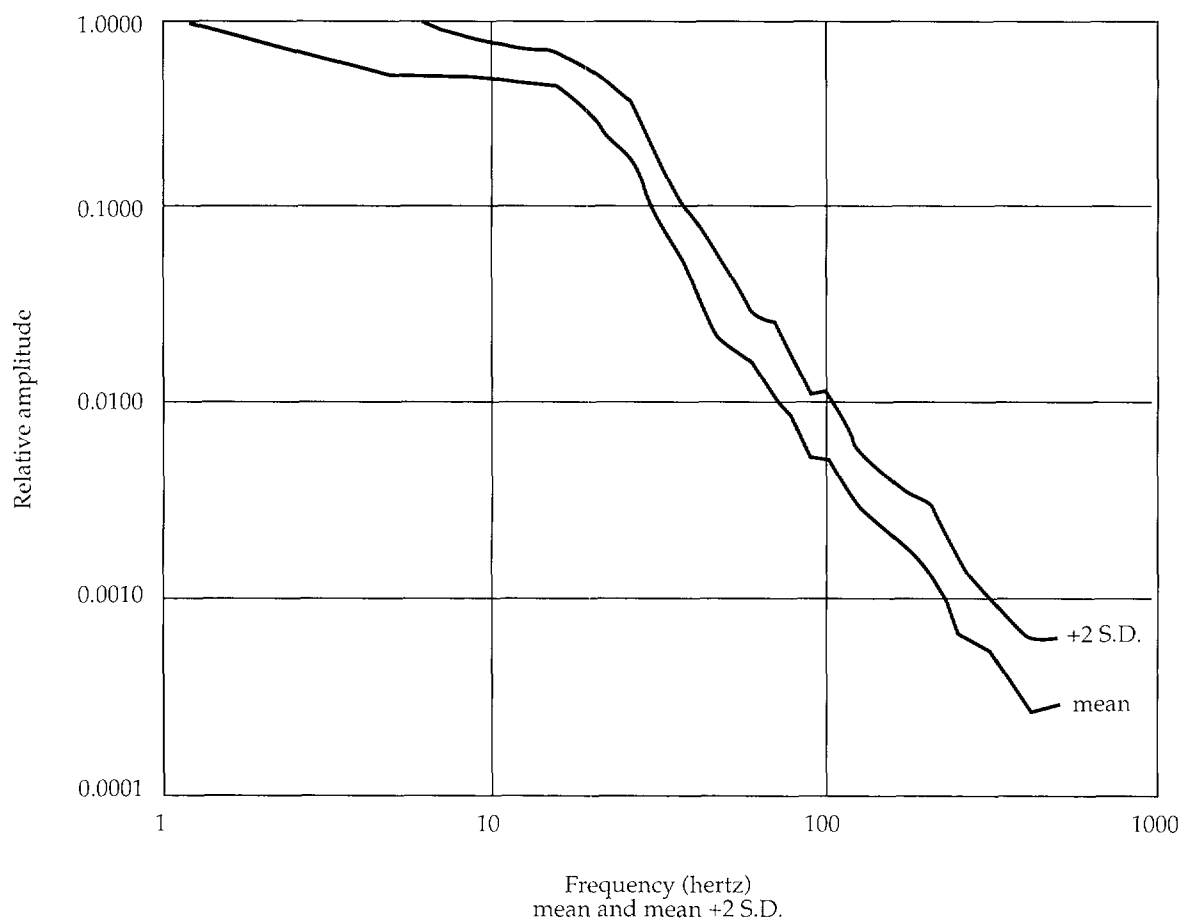
The following example from music illustrates the Fourier concept. A defined signal, or note, from an inexpensive violin made of thermoplastic would be different from that coming from a Stradivarius. The basic frequency would be the same from each violin, but the quality, or timbre, of the sound would be different. Each instrument would emit the basic frequency along with many harmonics, which are integral multiples of the basic frequency. The plastic instrument would produce harmonics different from those of the Stradivarius, and it would likely provoke immediate disapproval from a discriminating audience. An electronic sound system for the violins would have to be capable of delivering the composite signal, that is, the fundamental note and the pertinent harmonics of each instrument. The audience hearing the sounds through the system would then be able to tell which violin produced each note.

In electrocardiography, the discrimination involves signals that mean cardiac malfunction and those that mean electric normalcy. The system—electrodes, amplifier, and displayer—must obtain, increase, and present the signals faithfully, to allow accurate diagnoses. Like the sound system for the notes from violins, the system for electrocardiography must be able to function with signals that please as well as those that displease. Testing an electrocardiograph with a normal signal is, therefore, insufficient. A normal signal may not have the harmonics of an abnormal one: a notch denoting ischemia, for example, can have harmonics much higher than those of a normal QRS complex.^{23,24} Even when the distortion of a normal signal is unnoticeable, the distortion of an abnormal one might lead to inaccurate diagnoses.

The Fourier series provides details of the frequency content of periodic signals. These equations specify the series:

Figure 6.1 — Spectra of electrocardiographic frequencies.*

*Plot of the overall mean (lower line) plus two standard deviations (upper line) spectra from 203 ECG cycles and 10 subjects. This plot was produced by averaging the 20 lead-averaged spectra at a series of discrete frequencies (1.22, 4.88, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 150, 200, 250, 300, 400, and 500 Hz).



$$f(t) = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega_0 t + b_n \sin n\omega_0 t) \quad \text{Equation 6.1}$$

$$\text{where } a_0 = \frac{1}{T} \int_{t_0}^{t_0 + T} f(t) dt \quad \text{Equation 6.2}$$

$$a_n = \frac{1}{T} \int_{t_0}^{t_0 + T} f(t) \cos n\omega_0 t dt \quad \text{Equation 6.3}$$

$$b_n = \frac{1}{T} \int_{t_0}^{t_0 + T} f(t) \sin n\omega_0 t dt. \quad \text{Equation 6.4}$$

Equation 6.1 stipulates that periodic signal $f(t)$ can be considered a constant term a_0 added to an algebraic summation of sine and cosine waves of different amplitudes and frequencies. Amplitudes a_n and b_n are the peaks of the waves. The number n of each component in the summation of waves is a multiplier of the fundamental frequency ω_0 , which is measured in radians per second. The corresponding frequency f , in hertz, or cycles per second, is the radian frequency divided by 2π . Time t_0 marks the start of the signal, the period of which is interval T , or $1/f$.

To test the Fourier concept, a person could electronically sum the specified components to produce the signal. The Fourier series calls for an infinite number of harmonics, so practical compromise is necessary. For a particular signal, adding the tenth harmonic might enhance the fidelity to the original signal by less than one percent. Generating signals by adding many components is unusual in electronics, but it is certainly illustrative during consideration of Fourier analysis of waveforms.

For the experiment to work, the electronic summer of the Fourier components must be distortion-free. It must amplify each component equally, regardless of the frequency, and it must maintain the phase relations. Some of the components should be sine waves ($b_n \sin n\omega_0 t$) and some should be cosine waves ($a_n \cos n\omega_0 t$). The summer must maintain the 90-degree difference between the sine and cosine waves to prevent distortion. A constant voltage (a_0) is necessary in the summation if the original signal has more enclosed area above the abscissa than below it. Amplitude linearity, phase linearity, and bandwidth adequacy allow the summer to add the components without changing the relative ampli-

Figure 6.2 — Lead II with electromyographic artifact.



Figure 6.3 — Lead II with line frequency (60-hertz) artifact.

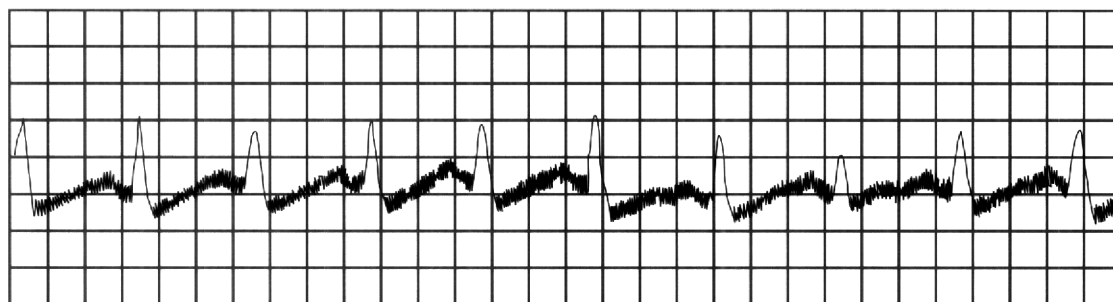


Figure 6.4 — Lead II with electromyographic and line frequency artifact and some baseline wander.



tudes and phases of the components. The signal delivered by the summer would thus be practically the original.

Another way to determine the harmonic content of a signal is to subject the signal to electronic analysis to obtain the spectrum. Figure 6.1 shows one type of spectral diagram in which the relative amplitude of each frequency in the periodic signal is clear. Some diagrams present spectral data in terms of power, with the ordinate scaled in decibels and the abscissa scaled in harmonics. An electrocardiographic signal is, however, not strictly periodic. In the course of a day, for example, the heart rate varies considerably.²⁵ Arrhythmic complexes may occur occasionally during that time, and the shape of some complexes may be different from that of others. The rate of occurrence of the variations seem to fit the so-called pattern of chaos.²⁶ Even if each PQRS complex in lead II is considered alone in time, a mathematic procedure such as the Fourier transform can disintegrate it into components with a continuous spectrum of frequencies and phases. A computerized procedure, called the fast Fourier transform, allows some spectral comparison of complexes, toward the detection of abnormalities.

6.3 Noise or Artifact

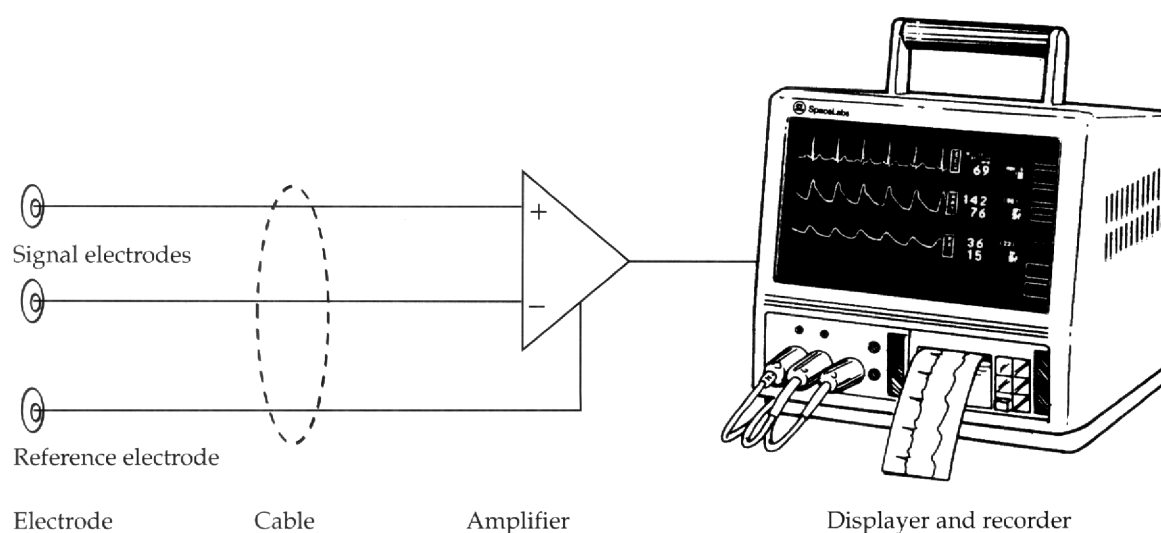
Signals other than cardiac constitute noise, or artifact, in the electrocardiogram. Such artifact may come from any of the millions of other muscles in the body, especially from those near the electrodes. One symptom in the cardiac distress syndrome is anxiety, which causes some contraction of various skeletal muscles. Electromyographic signals are therefore plentiful, and they can interfere at a time when electrocardiographic signals are considerably more important. Simple verbal reassurance may calm the patient and so diminish the muscle artifact in the electrocardiogram (Figure 6.2). Filtering in the amplifier can reduce some of the remaining artifact.

Another kind of noise, sometimes called 60-cycle artifact in the United States, comes from the circuit of power lines in and near the room in which the electrocardiogram is obtained. Many of the lines are invisible, hidden within walls and behind ceilings. The lines nevertheless cause minute electric currents through capacitive coupling. Although the coupled currents are small, they sometimes obscure small waves in an electrocardiogram (Figure 6.3).

The current at line frequency may come through inadvertent, resistive contacts instead of capacitive coupling. Even a tiny current at 60 hertz can be fatal; therefore, line frequency artifact in an electrocardiogram calls for immediate determination of the cause. Properly designed and maintained equipment is unlikely to cause harmful current, but vigilance is still the essence of safety. Allowing line frequency artifact in electrocardiograms to continue is unsafe because the artifact is indistinguishable from the record of noxious current. The same argument applies to inappropriate use of filters to remove the line frequency artifact. Common causes of the artifact are loose electrodes, faulty connections in the cable, and dried electrolyte. A relatively uncommon cause of artifact in electrocardiograms is electricity from a miswired receptacle or power cable.

Distinguishing between the two most common types of artifact is usually easy. The electromyographic type has irregular peaks and unequal zero-crossings; the line frequency type has virtually constant amplitude and frequency. Figure 6.4 shows an electrocardiogram that has electromyographic and line frequency artifact and some wandering of the baseline.

Figure 7.1 — Basic components of an electrocardiographic system.



7.0 ELECTRODES AND ELECTROLYTES

7.1 *Function in Overall System*

The fundamental components of electrocardiographic equipment are: electrodes, cable, amplifier, and displayer or recorder (Figure 7.1). The electrodes obtain the signals, the cable conveys them, the amplifier boosts them, and the displayer or recorder presents them. A person produces the signals, and a person will probably analyze them, perhaps with the aid of a computer. The design and use of each component should therefore involve electronic, biologic, and psychologic considerations.

7.2 *Goals in Design*

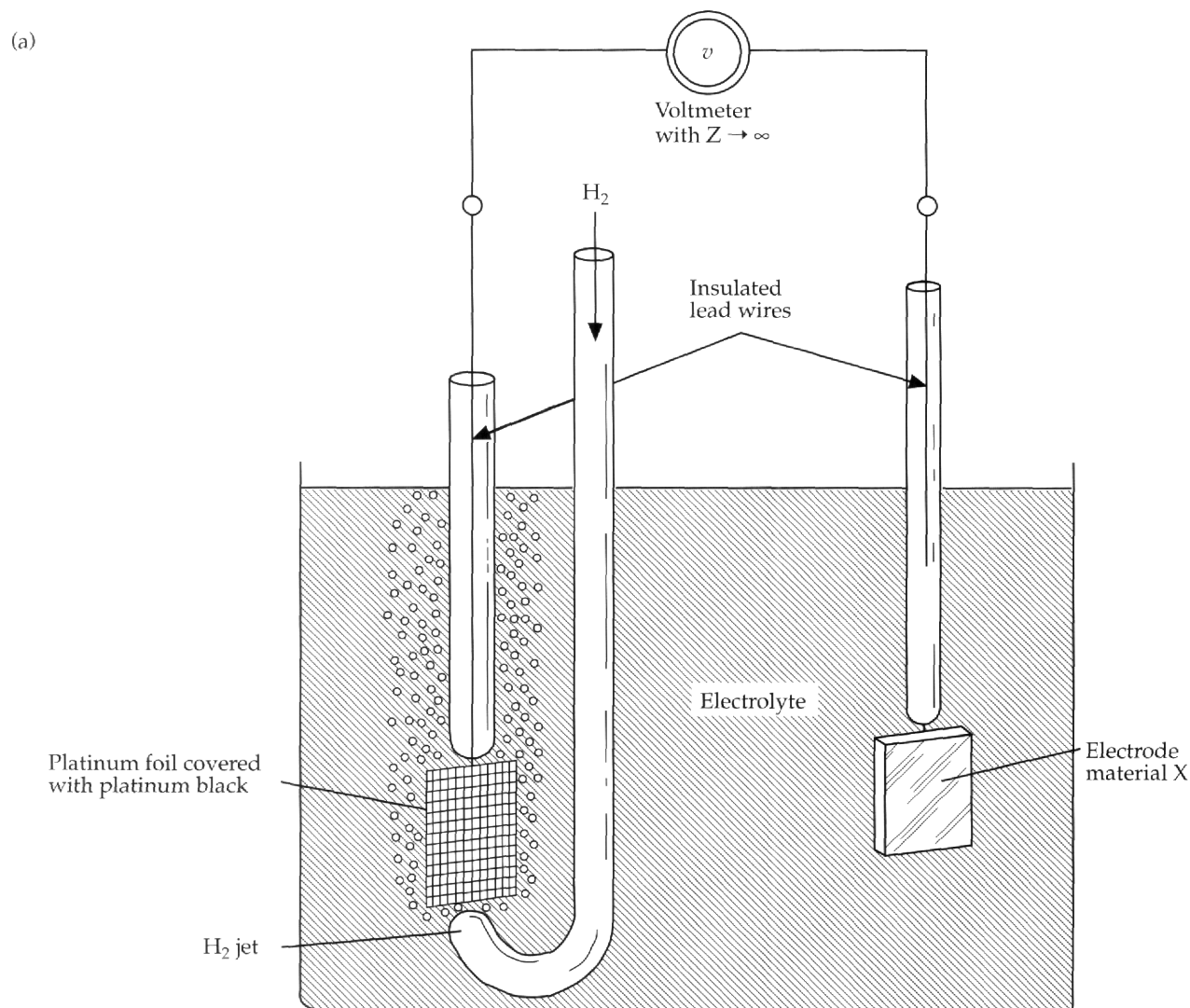
The main goal in the design of electrocardiographic electrodes is to provide absolutely safe, electrochemically stable, and psychologically acceptable contacts that obtain the signals of interest without introducing or allowing artifact. Many users would add the term inexpensive, and environmentalists would add biodegradable. Practical design cannot satisfy all the requirements, so reasonable compromises are necessary.

7.3 *Hazards*

No material in the electrode and in the associated electrolyte should be injurious in normal use. Chemical hazards include those related to toxicity and allergy. Mechanical hazards include pressure, which can cause vascular occlusion, and puncture, which can cause skin lesions. Infection is possible, although the proper use and disposal of single-use electrodes has essentially eliminated the risk of transferring infectious microorganisms from one person to another. Situations in which the electrodes remain attached for days or may be pressed against the skin by body weight increase the risk of chemical, mechanical, and microbial mishaps.

Hazards of iontophoresis and electrolysis are apparently insignificant when the bias currents at the input of the amplifier are very small, as in present-day electrocardiographic equipment. During electrosurgery, however, burns of the skin under electrocardiographic electrodes have occurred, which prompted the incorporation of special devices in the

Figure 7.2 — Half-cell voltage: (a) Circuit for measurement. (b) Measured values at 25° C.



(b)

Metal and reaction	Potential
$Al \rightarrow Al^{3+} + 3e^-$	-1.706
$Zn \rightarrow Zn^{2+} + 2e^-$	-1.763
$Cr \rightarrow Cr^{3+} + 3e^-$	-1.744
$Fe \rightarrow Fe^{2+} + 2e^-$	-0.409
$Cd \rightarrow Cd^{2+} + 2e^-$	-1.401
$Ni \rightarrow Ni^{2+} + 2e^-$	-0.230
$Pb \rightarrow Pb^{2+} + 2e^-$	-0.126
$H_2 \rightarrow 2H^+ + 2e^-$	-0.000 by definition
$Ag + Cl^- \rightarrow AgCl + 2e^-$	+0.223
$2Hg + 2Cl^- \rightarrow Hg_2Cl_2 + 2e^-$	+0.268
$Cu \rightarrow Cu^{2+} + 2e^-$	+0.340
$Cu \rightarrow Cu^+ + e^-$	+0.522
$Ag \rightarrow Ag^+ + e^-$	+0.799
$Au \rightarrow Au^{3+} + 3e^-$	+1.420
$Au \rightarrow Au^+ + e^-$	+1.680

cables and amplifiers of electrocardiographic equipment to virtually eliminate the hazard.

Some electrodes pose a hazard by not being able to obtain electrocardiographic signals after an attempt at defibrillation. The voltage for defibrillation is large and causes considerable current through the electrodes. That current increases polarization, resulting in an abnormal voltage at the electrodes that lingers after the current stops. When that voltage is enough to saturate the amplifier, amplification of electrocardiographic signals is impossible. Saturation may be slow in dissipating even after the polarization decays to a very low level. Thus, the saturation can cause an unfortunate interruption of electrocardiographic information.

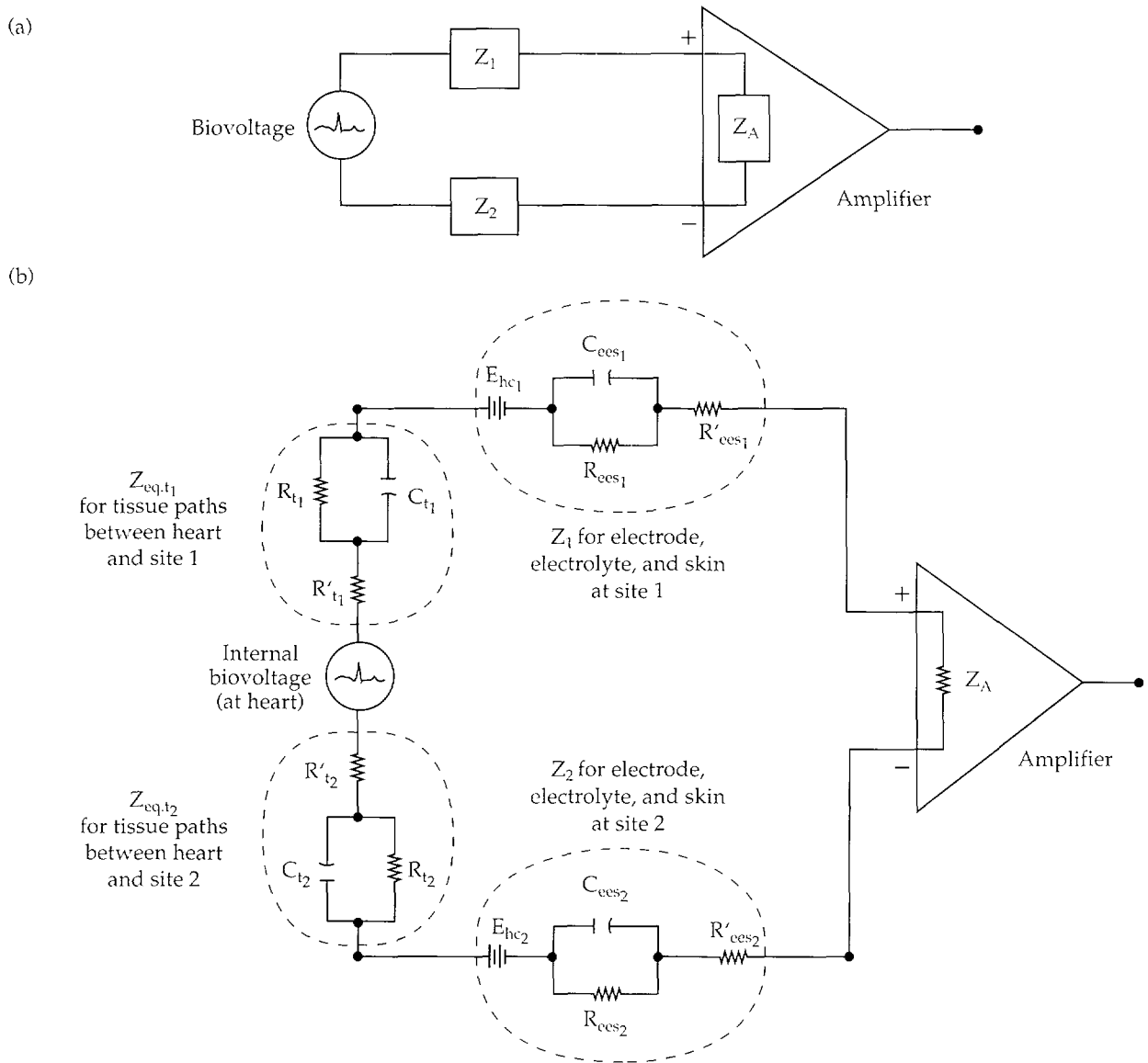
Theory holds that an electrode can be perfectly polarizable, which means that it would respond to current as a perfect capacitance would. A perfectly nonpolarizable electrode, needed for most electrocardiographic applications, would respond as a perfect conductor would. Electrodes in the real world are imperfect, of course. Even the best electrocardiographic electrodes are polarizable to some extent, so the circuits representing them include both resistance and capacitance.

7.4 **Stability**

Electrochemical stability refers to the half-cell potential and to the impedance of the electrode in contact with the tissue. The half-cell potential arises when an electrode and electrolyte are joined. To measure the potential difference of the half-cell, a meter, which should have infinitely large impedance, requires another connection to the electrolyte to complete the circuit. That second connection causes another interface and another voltage. Each of the two voltages is, figuratively, half a cell, although the two are not necessarily equal. Making one half-cell the standard, with a designated voltage of zero, simplifies measurement of the other half-cell voltage. The hydrogen electrode is the standard.²⁷ Figure 7.2a offers a pictorial representation of the measurement of half-cell potential, and Figure 7.2b lists the half-cell voltages of some materials considered for, or used in, medical electrodes.

In usual electrocardiography the electrodes have essentially the same composition and electrolyte. Two of the electrodes obtain the signal of interest. If the two electrodes and their interfaces were electrically identical, the half-cell voltages would be equal. The amplifier, which increases the difference in potential delivered to its input terminals, would then

Figure 7.3 — Equivalent circuits. (a) Series circuit, simplified. (b) Series-parallel circuit, with half-cell voltages and equivalent impedances.



boost only the signal of interest because the difference in the half-cell voltages would be nil. That desirable cancellation of half-cell voltages depends on equality, a rare condition in practice. The difference in the voltages is the slowly varying offset, which enters the amplifier along with the signal of interest. Disparity in electrode corrosion, impurities in the electrode and the electrolyte, exudates from the skin under each electrode, and temperature at each electrode site are among influences on the offset voltage. Much of the wander in electrocardiograms occurs because of the instability, or drift, of that voltage.

7.5 *Impedances*

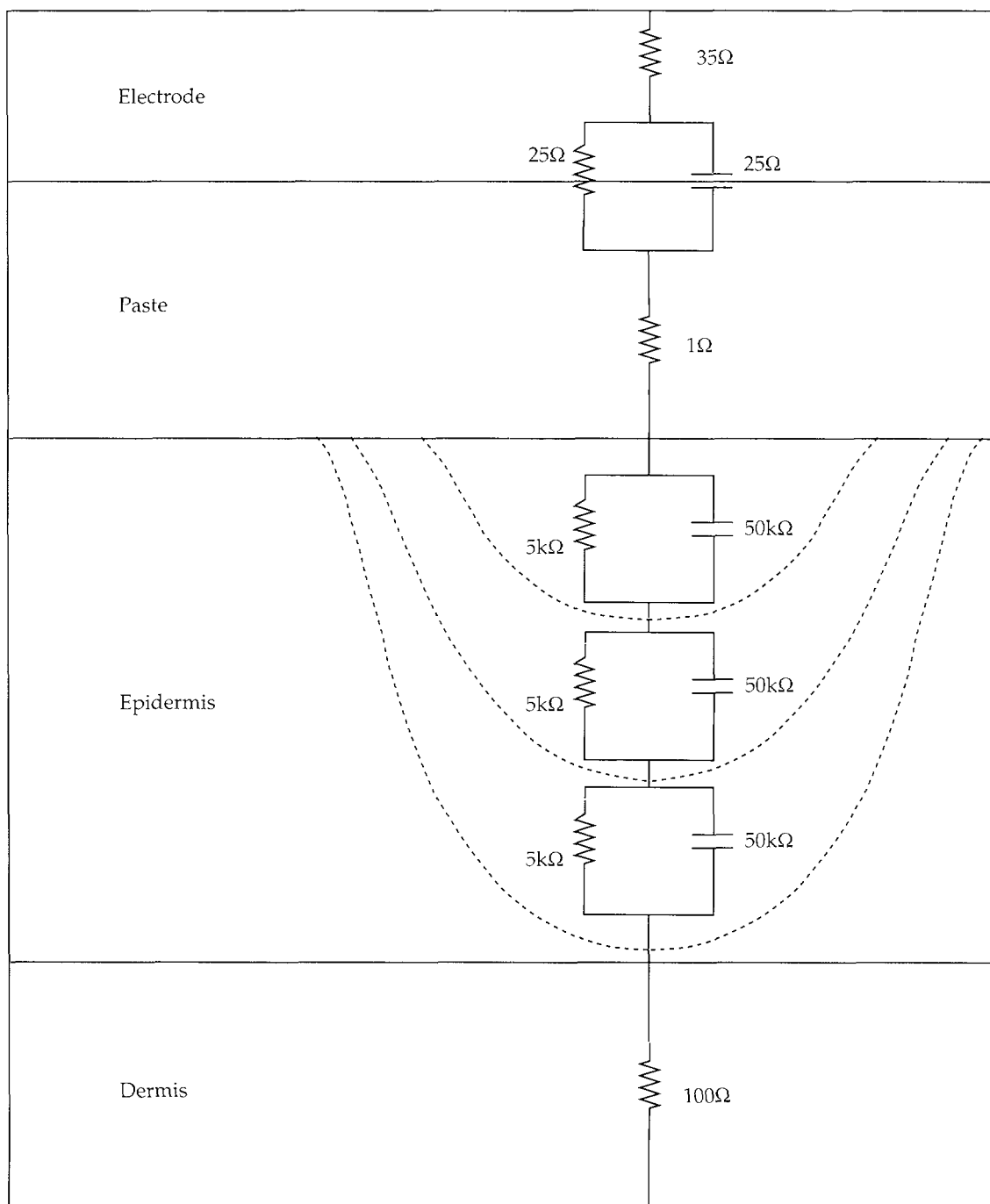
Certain requirements pertaining to the impedance of the electrode, electrolyte, and skin come from consideration of the circuit shown in Figure 7.3a. In an ideal situation, impedances Z_1 and Z_2 are zero, and Z_A is infinitely large so that all the voltage from the biologic source transfers to the terminals of the amplifier. In a real situation, Z_1 and Z_2 are certainly not zero, and Z_A has a practical limit. Although Z_A is relatively constant over the specified bandwidth of the amplifier, Z_1 and Z_2 vary in response to mechanical, chemical, and thermal influences, such as those mentioned above in relation to the instability of half-cell voltages. When Z_1 and Z_2 increase, more of the voltage of interest drops across them, leaving less for the input of the amplifier. The situation would be less problematic if the variations in impedance were predictable and if they were the same for all frequencies in the electrocardiographic bandwidth. Figure 7.3b offers a revision of the circuit in Figure 7.3a to show some practical detail. Each symbol in the circuit might well have an arrow through it, to denote variability. Half-cell voltages E_{hc1} and E_{hc2} produce a direct current in the circuit. The electrocardiac waves introduce another direct current and a summation of sinusoid currents in a certain range of frequencies, in the Fourier sense. The combination of resistances and capacitances in impedances Z_1 , Z_2 , Z_{eQt1} , and Z_{eQt2} further emphasizes that each impedance is frequency sensitive. A basic requirement is, therefore, that the magnitude of Z_A be much greater than that of the combination of all the other impedances at all frequencies in the bandwidth necessary for reasonably accurate presentation of the electrocardiographic waves.

The usual frequency for measuring such impedances, relative to electrocardiography, is 10 hertz. Figure 7.4 provides some typical values for a silver/silver chloride electrode of 1 square centimeter used with an electrolytic paste. The dotted lines in the epidermis refer to the reduction in impedance by abrading the skin.

7.6 *Psychologic Acceptability*

Electrodes and electrolytes produce only minor problems of acceptability if the patient understands the importance of obtaining the electrocardiographic signals. A patient afraid of being wired to electromedical equipment might respond well to verbal assurance that the equipment is harmless. Some patients whose electrocardiac signals are monitored for days may complain of the discomfort of attached electrodes and the

Figure 7.4 — An equivalent passive circuit showing typical impedances at 10 hertz.



tethering to the devices. Recent claims related to cellular telephones have prompted some patients to ask about the safety of wireless, or telemetered, systems.

7.7 ***Electrodes in Use***

Figure 7.5a presents examples of plate and bulb electrodes. The material often used in such electrodes is German silver, which is an alloy of zinc, copper, and nickel. The large area of a plate electrode in contact with the electrolyte and skin reduces the impedance. Suction created by squeezing the rubber bulb will keep the bulb electrode, or Welch cup, in place. The suction electrode is especially convenient in obtaining chest leads sequentially. Electrodes for patients in intensive coronary care, for persons in an exercise test in cardiac evaluation, and for astronauts are usually those typified by the electrodes in Figure 7.5b. The silver/silver chloride component, formed by electrochemically depositing a thin layer of silver chloride onto silver, is in contact with the electrolytic gel, semi-solid material, or soaked foam. In the recessed type of electrode, a column of electrolyte provides contact. Electrodes for persons who are physically active have such special materials and constructions to reduce the so-called motion artifact caused by distortion of the layers of charges in the electrolyte adjacent to the electrode.²⁸

Flexibility of the conductive element is a significant feature of electrodes of certain polymers or elastomers made conductive by the inclusion of screens, wires, or particles of metal or carbon. Fabrics with conductive strands form another category of flexible electrodes. Figure 7.5c shows some single-use, flexible, adhesive electrodes that are made of hydrophilic polymer. Water and ions in the polymer provide the necessary conductivity.

Other types of surface electrodes, such as the dry, the insulated, and the carbon, have features that make them appropriate in special situations. Monitoring the electrocardiographic signals of a severely burned person or a premature infant may be feasible only with a special type of electrode.

The offset voltage between two suction electrodes on the inner forearm has a range of 9 to 102 millivolts. Between plates of 3x5 centimeters at various locations on the body, the voltages are "half the millivolt values for the bulbs."²⁸ Table 7.1 lists the voltages measured for five days between electrodes connected by electrolyte.

Figure 7.5 — Electrocardiographic electrodes: (a) Plate and bulb electrodes. (b) Single use, long-term electrodes. (c) Single use, short-term electrodes.

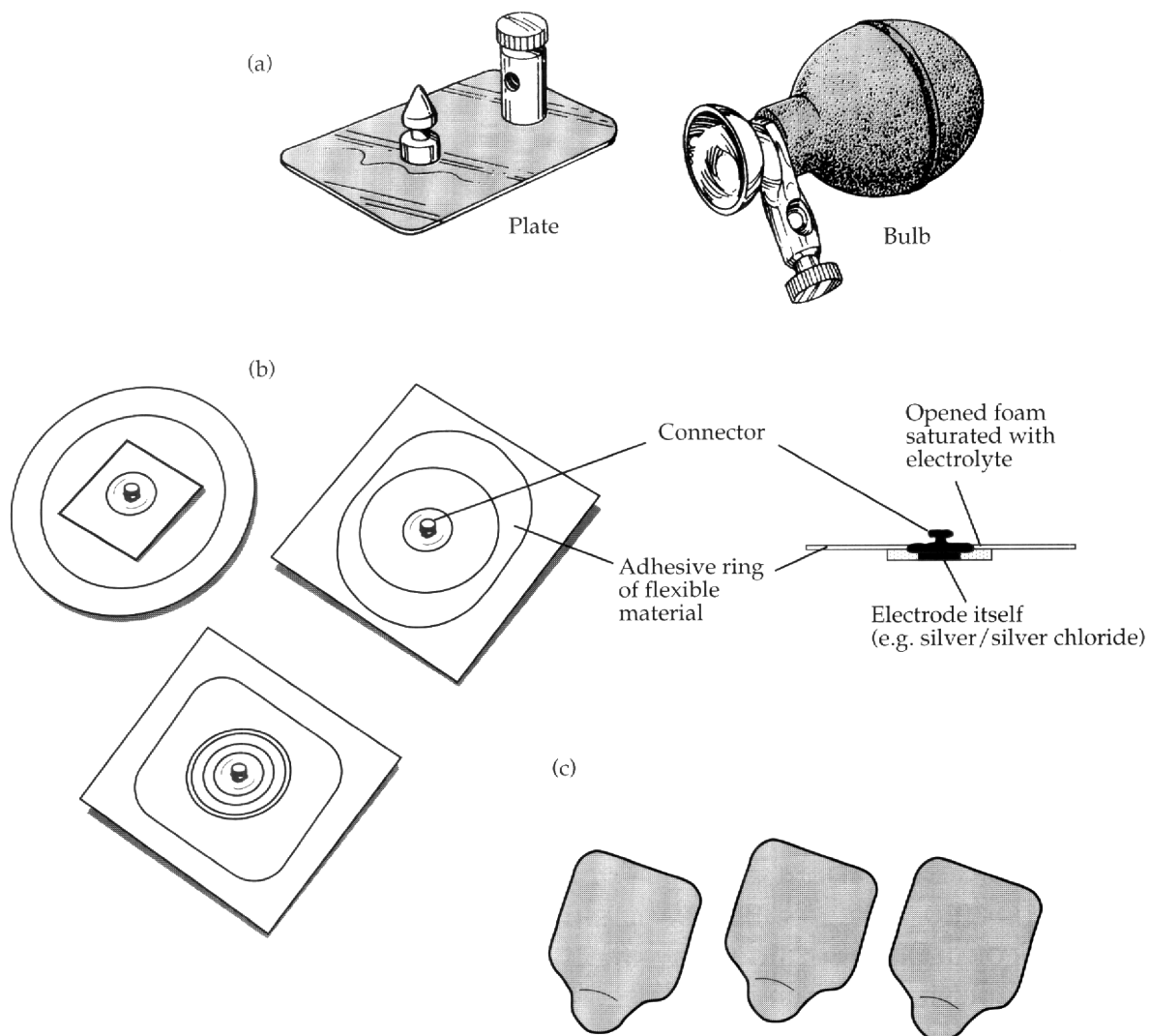
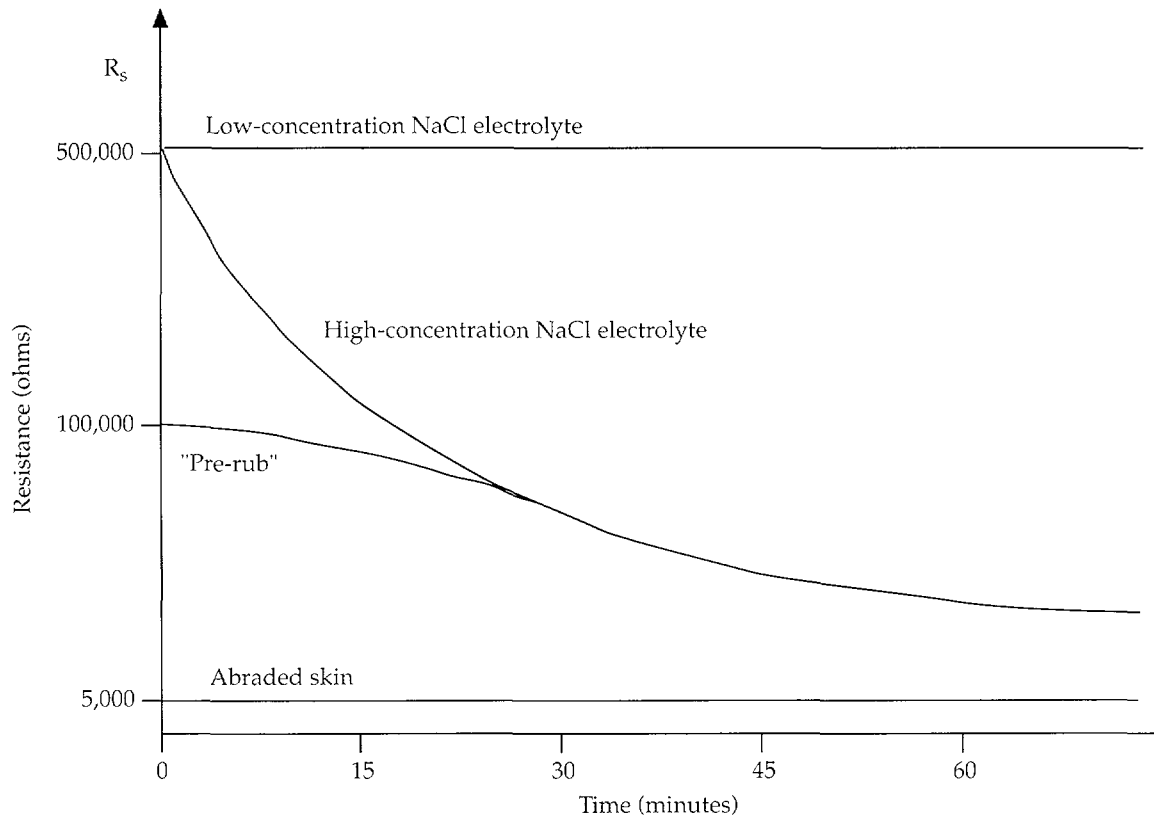


Table 7.1 - Voltages measured for five days between electrodes connected by electrolytic gel.

	Day 1			2			3			4			5		
	Avg.	Hi	Lo	Avg.	Hi	Lo	Avg.	Hi	Lo	Avg.	Hi	Lo	Avg.	Hi	Lo
Silver/Silver Chloride	2.57	7.50	0.53	0.79	2.80	0.05	0.42	1.26	0.07	0.32	0.90	0.02	0.4	1.51	0.2
Brass	8.65	28.9	0.23	10.6	34.8	1.01	35.3	80.3	2.35	29.5	71.0	5.65	21.3	58.8	1.00
Nickel	11.8	31.7	0.37	15.9	46.1	0.93	17.0	49.6	.01	21.9	56.0	.05	28.5	57.0	2.0
Stainless Steel	51.7	192	0.25	75.0	196	0.21	24.4	74.7	0.15	14.9	96.0	0.13	0.13	0.24	0.02

Figure 7.6 — Variation of resistance of skin/electrolyte/electrode with time.



7.8 *Electrolytes in Use*

An electrolyte is an ionizable substance in solution. Relative to the measurement of biovoltages, however, an electrolyte is the solution itself, regardless of the form of the solution. Electrolytes are the pastes, gels, creams, jellies, and semi-solids that are interposed between electrodes and skin to obtain better electric contact.

Water is the main ingredient of most electrolytes in electrocardiography. Ionic salts, such as potassium chloride and sodium chloride, are common additions. Surfactants, which lower the surface tension to "make water wetter," help lower the impedance of the connection. Humectants attempt to keep the electrolyte wet during the specified shelf life and period of use. Fungicides and germicides help control microorganisms. Thickeners keep electrolytes from running when they are applied.

Even a strong electrolyte needs time to work, as Figure 7.6 illustrates. The electrolyte with a low concentration of sodium chloride (0.5% or so) did not provoke any change in skin resistance within an hour. The elec-

trolyte with a relatively high concentration (5 to 10%) of the chemical caused a considerable decline in resistance. Rubbing the skin lowered the resistance, and abrading the skin lowered the resistance much more. Although such engineering data may be technically convincing, abrading is not necessarily the universal answer. The thin, fragile skin of an 84-year-old patient, for example, may neither need abrasion nor be able to withstand it.

8.0 AMPLIFIERS

8.1 *Function in Overall System*

The fundamental task of the amplifier is to boost the signal to a level that allows presentation of the amplified signal with acceptable fidelity. The presentation may be on, in, or from a device such as a chart recorder, oscilloscope, or liquid-crystal screen.

8.2 *Gain*

The voltage gain of the amplifier in a typical electrocardiograph is 1000. Perhaps more illustrative in this regard is that the sensitivity of the entire system is typically 10 millimeters per millivolt. A voltage of 1 millivolt at the input therefore causes a display 10 millimeters above a horizontal level selected by the operator. Many electrocardiographs and monitors provide sensitivities of double and half the usual 10 millimeters per millivolt, sometimes denoted as $\times 2$ and $\times 1/2$, respectively, on the operator's panel. Some systems allow selection from five sensitivities, and some provide automatic control so that the trace does not exceed a certain distance in either direction.

If a galvanometer or pen motor is in the system, the amplifier must provide a considerable current to correspond to the small voltage obtained from a person. The amplifier thus has what may be called transconductance gain, insofar as the output of current divided by the input of voltage renders a transfer, or gain, that has units of conductance at a frequency in the middle of the range. If an oscilloscope, liquid-crystal screen, or other voltage-sensitive device is the display, the amplifier must provide voltage gain to raise the input to a level sufficient to properly stimulate the device.

8.3 **Linearity**

Linearity is a requirement of the overall performance of the electrocardiograph and electrocardiographic monitor. A steadily changing voltage should cause a linear deflection upward if the voltage is positive, and downward if the voltage is negative. The magnitude of the slope of the downward deflection should be the same as that of the upward one.

The amplification should be linear if the recorder or displayer operates linearly. If the recorder or displayer operates nonlinearly, the amplification must compensate nonlinearly to produce a satisfactory presentation. A common specification for the entire system is linear range. An example is ± 5 millivolts $\pm 10\%$, which means that an input voltage steadily increasing from -5 millivolts $\pm 10\%$ to $+5$ millivolts $\pm 10\%$ would cause a linear presentation on the screen or paper if the rate of increase, or slew rate, is below the specified maximum.

8.4 **Bandwidth**

Synthesizing a normal lead II by summing components would require a constant voltage and about seven harmonics. Amplification and display of a normal lead II would, accordingly, require a bandwidth extending from 0 to about 100 hertz, depending on the desired fidelity. Many current standards for diagnostic electrocardiographs specify a bandwidth extending from 0.05 hertz to 100 hertz, which are the corner frequencies f_L and f_H in a plot of voltage gain with respect to frequency. At each of the two frequencies, the decreasing gain is 3 decibels below A_{mid} , where A_{mid} is the amplification at a frequency near the middle of the range (Figure 8.1).

Because Fourier analysis shows that a constant is involved in most types of electrocardiographic signals, the specification of a pertinent bandwidth that does not extend from zero seems astonishing. The ST segments, for example, can have diagnostically important deflections that involve very-low-frequency phenomena; therefore, the need for adequate response at very low frequencies is clear. At the other end of the electrocardiographic spectrum are the high frequencies, such as those responsible for steep slopes and notches in waves. Accurate exposition of notches in an electrocardiogram requires a bandwidth having an upper frequency of several thousand hertz.

Arguments against using a bandwidth beginning at zero frequency, or dc, usually refer to problems with electrodes and techniques in affixing electrodes. Arguments against extending the bandwidth to 5000 hertz, for

Figure 8.1 — Determining bandwidth from gain-versus-frequency curve.

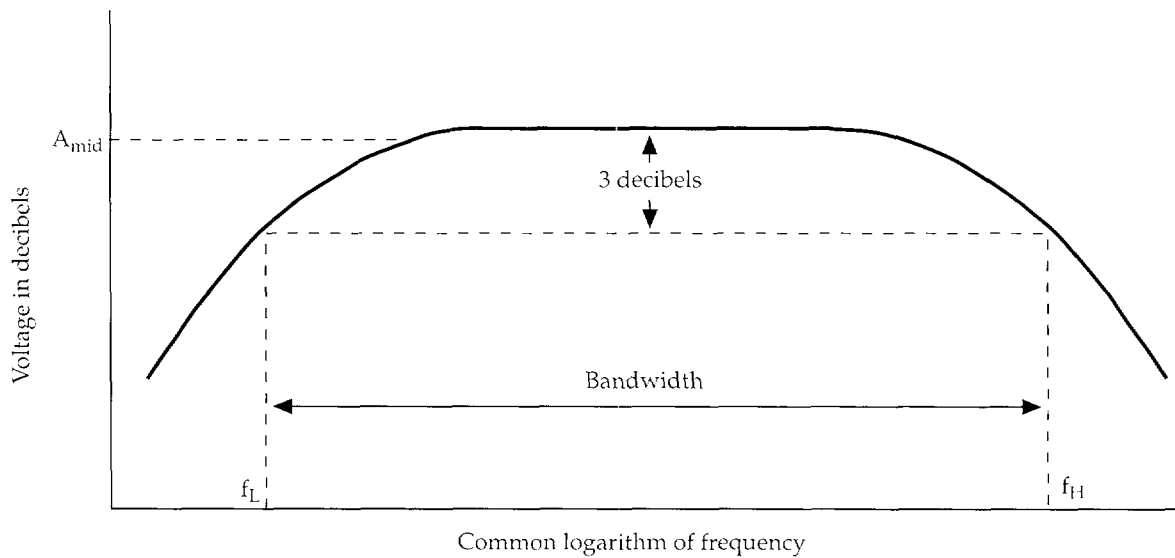
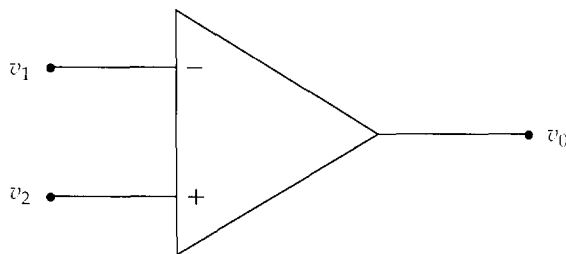


Figure 8.2 — Equations for output voltages: (a) An ideal differential amplifier. (b) A real differential amplifier.



$$(a) \quad \begin{aligned} v_0 &= A_d v_d \\ \text{where: } A_d &= 1/2 (A_1 - A_2) \\ v_d &= 1/2 (v_1 - v_2) \end{aligned}$$

$$(b) \quad \begin{aligned} v_0 &= A_d v_d + A_c v_c \\ v_0 &= A_d v_d [1 + (1/\text{CMRR})(v_c/v_d)] \end{aligned}$$

$$\begin{aligned} \text{where: } A_d &= 1/2 (A_1 - A_2) \\ A_c &= 1/2 (A_1 + A_2) \\ v_d &= 1/2 (v_1 - v_2) \\ v_c &= 1/2 (v_1 + v_2) \\ \text{CMRR} &= |A_d/A_c| \\ v_1 &= v_c + v_d \\ v_2 &= v_c - v_d \end{aligned}$$

example, include reference to possible artifact from muscles and electric equipment and the inability of a chart recorder that depends on a galvanometric device to move a stylus across a paper with sufficient speed. The compromise, 0.05 to 100 hertz, retains most of the diagnostic value of the electrocardiogram while reducing artifact. Some wandering of the baseline stops when the lower frequency of the bandwidth is moved from 0 to 0.05 hertz. Some artifact caused by muscles and electric equipment vanishes when the upper frequency is lowered to 100 hertz.

The typical bandwidth of electrocardiographic monitors in their monitor mode is narrower than that of electrocardiographs. A monitor may have a bandwidth from 0.5 to 40 hertz, for example. The limited bandwidth still allows surveillance of ventricular rate and rhythm, which can be determined if just the R waves are distinguishable. Electrocardiographs, however, should provide information of more diagnostic value by accurately displaying all waves. The distinction between the two types of equipment does not always hold in practice. Some monitors offer a mode of operation that provides a diagnostic bandwidth; on the other hand, some diagnostic electrocardiographs offer a mode of operation that narrows the bandwidth. Denoting the bandwidth on the screen of the monitor or on the paper from the electrocardiograph could be very informative for the person examining the signals.

8.5 ***Input Impedance***

The ratio of the magnitude of the input impedance of the amplifier to that of the combined impedances of the skin, electrolyte, electrode, and wire pertaining to each connection is important. That ratio should be very large at all frequencies in the signal to enable almost all the signal to transfer to the amplifier. A recent standard calls for a minimum impedance (magnitude) of 2.5 megohms, from dc to 100 hertz, over the range of permissible offset voltages related to the electrodes.²⁹

8.6 ***Common Mode Rejection***

The typical amplifier in electrocardiography has a differential input, which means if the amplifier is ideal, that the output corresponds to only the difference between the signals at the two posts of the input. When the signals are equal, the output is zero. In mathematic terms the output is $A_d v_d$, where A_d is the voltage for gain for differential signals and v_d is the differential signal. Relative to the "+ input," the voltage gain is A_1 and, relative to the "- input," the voltage gain is A_2 . An expression for A_d is therefore $(1/2)(A_1 - A_2)$. If A_1 and A_2 are equal in magnitude but opposite in sign, A_d has the magnitude of either A_1 or A_2 . Because the input voltage v_1 is v_d and v_2 is $-v_d$, and expression for $v_1 - v_2$ is $2v_d$, which means v_d is $(1/2)(v_1 - v_2)$. Figure 8.2a summarizes the operation of an ideal amplifier.

A real amplifier, notably imperfect, delivers an output of $A_d v_d$, but with at least two other voltages: $A_c v_c$ and v_{an} . Common-mode gain A_c ,

which is $(1/2)(A_1 + A_2)$, increases common-mode voltage v_c , which is $(1/2)(v_1 + v_2)$. Voltage v_{an} refers to the noise produced by components in the amplifier. Proper design and maintenance can make v_{an} insignificant in comparison with the other voltages at the output (Figure 8.2b).

The absolute value of the ratio of A_d to A_c is, by definition, the common-mode rejection ratio (CMRR). A similar term, expressed in decibels, is common-mode rejection (CMR), which is 20 times the common logarithm of CMRR. For a CMRR of 100,000, for example, the CMR is 100 decibels.

A voltage at line frequency is likely to be common to the two voltages at the input of the amplifier. Another likely, troublesome condition is imbalance of the impedances pertaining to the skin, electrolyte, electrode, and wires for each of the two connections. Specifications of a minimum CMR thus pertain to the frequency of the power-line voltage and the imbalance of the impedances of the connections to the patient.

8.7 Features for Electric Safety

Electrical isolation from the hot side of the power line and from "earth ground" is very important in trying to prevent harm to a person connected to, operating, or otherwise in circuit with an electrocardiograph or monitor that is energized by way of the power line. The patient at highest risk is one who has a conductor, such as a catheter filled with saline solution, that leads from a point outside the body to one inside the heart. For that patient, an electrocardiographic instrument must have an electrically isolated input. Complete isolation from power lines and earth ground is impossible, however, in places electrocardiographs and monitors are normally used. The standards acknowledge that fact by specifying maxima for currents through the theoretically isolating barriers of electromedical devices. Although a current leaking through a barrier is small, it can be lethal.

A leakage current exists when a patient is connected to earth ground and a line-powered device. The pertinent standards call for measurement of the current in a specified impedance connected between earth ground and each conductor that would connect a person to the device. If the current exceeds the specified maximum, the equipment fails the test. Another leakage current is one that would exist if the person became connected to the "hot side" of the power line and an electromedical device. The pertinent test includes measuring the current in a specified im-

pedance connected between the hot side of the power line and each conductor that would connect a person to the device. Yet another leakage current to be measured is one that would be caused by voltages between the conductors connecting the device to a person. The test includes measuring the current in a specified impedance connected between one nonreference connection and each of the other connections. Each test is really two: one when the grounding connection of the power cable of the electromedical device is intact; and the other when the connector is not intact. The maximum current set for one condition is usually not the same as that for the other condition.

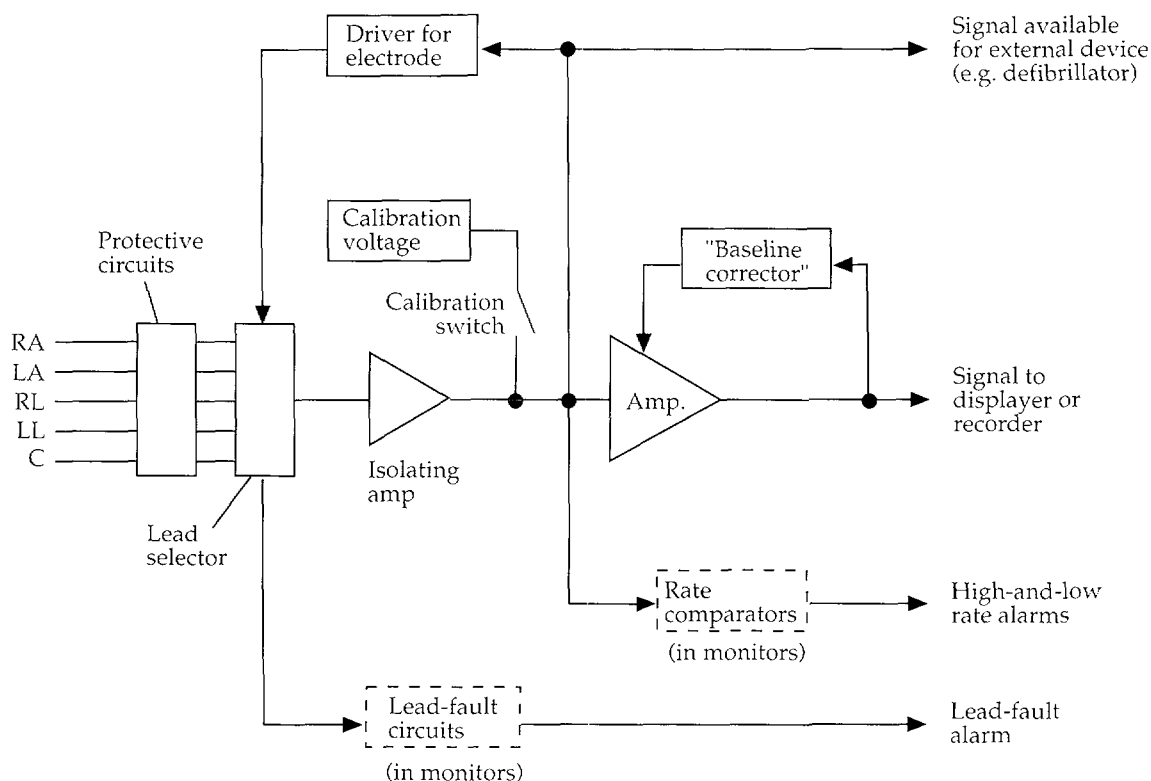
Electromedical equipment must pass even more tests before it can be judged electrically safe under the specifications of present standards such as those of the American National Standards Institute (ANSI), National Fire Protection Association (NFPA), and Underwriters Laboratories (UL). Some standards are particularly informative in that they offer explanations for the specifications.

Several means of isolating an amplifier enough to meet the specifications of standards are noteworthy here. Simply using batteries to provide power is one way to avoid connection to the power line. Advancements in regular and rechargeable (primary and secondary) batteries have made powering by battery a reasonable consideration. If the power required for technically and economically satisfactory operation of the system is such that battery power must be dropped from consideration, some choices in electromagnetic isolation merit attention.

A transformer can electromagnetically isolate the electrocardiograph or monitor from the power line. All the necessary power would have to come through that transformer, the cost of which increases with its electric ratings. Using a transformer to provide isolated power to just the first stage of the amplifier and using a photoelectric isolator or another transformer to transfer the signal from the first to the second stage can lower the cost of the system.

Protection of equipment is another consideration. An electrocardiograph that failed because it received a large voltage during a defibrillation attempt would provide no information at a critical time. A monitor that stopped working after receiving energy from an electrosurgical unit would fail to provide important information during surgery. In some devices, high energy from either defibrillators or electrosurgical units would damage components in the amplifier, rendering the system very dangerous.

Figure 8.3 — Block diagram of electrocardiographic amplifier.



Several manufacturers include protective circuitry in the cable leading to the amplifier, instead of putting it in the housing containing the amplifier. Whatever the location, the circuitry must drastically reduce high voltages and radio-frequency currents. The block identified as protective circuitry is understandably first in the series-parallel array of functional blocks shown in Figure 8.3.

A simple neon bulb connected from each incoming line to the reference point affords some protection by changing from a very high resistance to a much lower one when a high voltage is impressed across it. At its lower resistance, the bulb sustains a voltage of approximately 60 volts. The bulb's increased ionization and series resistance in the cabling leading to the amplifier reduce the high voltage to approximately 60 volts across the bulb. A similar device, called a spark gap, can serve as the voltage-controlled switch that is useful in protecting circuitry against high voltages.

An easy way to limit the currents from electrosurgical units is to place an inductance, sometimes called a radio-frequency choke, in series with the wire from each electrode to the amplifier. Connecting a filter involving resistances and capacitances in each line is another way of impeding high-frequency currents. The impeded currents should be too small to cause burns of the skin at the electrocardiographic electrodes or to damage components in the amplifier.

8.8 ***Other Features and Functions***

Figure 8.3 presents a block diagram of an electrically safe amplifier having an isolating stage and an amplifying stage. Each stage may participate in the function of the other; the separation in the figure simply emphasizes the two functions. The connection between the two stages may be electromagnetic, photoelectric, or electric, in keeping with the type of power supply and the specifications of electric safety.

The protection circuits depicted in Figure 8.3 should function as described in Section 8.7. The lead-selector sends the chosen signal to the amplifier and to the lead-fault circuits, if any. For chest leads, the lead-selector provides the Wilson terminal as the reference. Yet another function of the lead-selector is the routing of voltage from the driver to the reference electrode in systems involving an electronically modified reference, as in "right-leg drive." The driven reference helps reduce noise in the signal of interest. The pertinent circuit derives a common-mode voltage from two or more signal electrodes and applies that voltage, inverted, to the reference electrode.

Lead-fault circuits determine the resistance or impedance of a connection to the patient and initiate an alarm when the measured amount becomes so high that it signifies a loose, detached, or otherwise faulty connection. One technique uses direct current for the measurement, limiting that current to picoamperes to minimize disturbance of ionic situations at the electrodes. Another technique uses current alternating sinusoidally at 100 kilohertz or so, with an amplitude higher than that permissible in the direct-current method.

By comparing the existing rate of the heartbeat to upper and lower limits set by hand or derived electronically, the rate comparators can determine causes for alarm. The existing, or current, rate is usually an average over several beats, sometimes derived by electronically inverting the mean of the periods measured between R waves of five successive complexes.

The baseline-corrector has a potentially misleading name. Correction implies that something is made accurate. A baseline in regular electrocardiography is only artificially zero, but many measurers of the amplitudes of waves regard the baseline as zero volts. The purpose of the circuit in question is to keep the presentation of the signals within certain bounds on the paper or screen. Too large a signal at the input of the amplifier may saturate it, causing the trace on the paper or screen to go out of bounds. One function of the block marked baseline-corrector is to desaturate the amplifier, which usually means discharging the coupling capacitors. Another function of the block is to adjust against objectionable drift of the baseline, sometimes called baseline wander.

Signals resulting from electronic pacing create several challenges for the designer of a monitoring system and for the interpreter of the electrocardiographic display on the system. The duration of each pulse delivered to the heart from an electronic pacemaker is about one millisecond. The corresponding pulse obtained on the skin is a tall, narrow wave, or spike. Accurate display of the spike is possible only if the amplifier and displayer have adequate response at high frequencies. The pacing signal is small or absent in monitoring systems in which the higher corner-frequency is only 35 hertz or so.

Pacing spikes, or pacemaker artifact, can cause errors in rate-measuring circuits because the spikes may be counted as R waves. To reduce the error in determining heart rates, electronic circuitry can differentiate the spikes, and many other kinds of waves, from R waves. One method of determining which wave to count relies on programming in the digital domain, sometimes called the software solution. In certain systems that suppress the spikes, an electronically created pulse appears in the electrocardiographic display to mark the time of each pacing spike. That displayed pulse is not the pacing signal obtained on the skin, but an artificial one that the system creates to mark the time of the spike.

9.0 DISPLAYERS

9.1 *General Requirements*

Electrocardiographic signals vary with time; therefore, the devices used to present the signals must have a means for moving either the medium on which the record is produced or the entity that causes the medium to

accept information. A common example is the chart recorder, in which the paper moves and the stylus causes the trace. A contrasting example is the cathode-ray tube, in which the electron beam moves and the medium, the screen of the tube, is stationary. The displayer must present the signal with fidelity, that is, the mechanical, electrical, and visual characteristics of the displayer must allow the presented signal to be reasonably free of temporal and spatial distortion.

9.2 ***Electromechanical Devices***

Many electromechanical devices for producing electrocardiograms are essentially chart recorders. The chart is paper that is forced to move under a stylus designed to mark the paper.

A heated stylus, for example, marks special paper in which ink is released thermally. An inking stylus, or pen, either writes on the paper or blows ink onto it. An electrostatic stylus uses an electric field to mark special paper. In many devices the interface of the stylus and the paper involves significant friction, which is an important consideration in the design of the electromechanical driver of the stylus.

The electromechanical driver, basically a restrained motor, must be sufficiently responsive to move the stylus across the paper fast enough to record sinusoid signals of 100 hertz. Current moving through the electromechanical driver, such as a galvanometer or permanent magnet moving-coil (PMMC) assembly, causes the movement (Figure 9.1). By creating a magnetic field that reacts with that of the permanent magnet, the current in the moving coil produces a torque that makes the stylus move across the paper. Reversing the current reverses the field; therefore, the torque reverses.

For the stylus to move, other parts of the system must move, as is evident in Figure 9.1. Because of the mass, inertia is a characteristic that must be included in a model of the system. Friction at the pivotal points of the moving coil and at the interface of the stylus and paper is another consideration in developing the model. The force provided by the spring or other device that restores the coil to a selected position is yet another consideration. In electric terms the model is an inductance-capacitance-resistance one, and in mathematic terms, the model is a second-order differential equation.³⁰ Figure 9.2 shows three categories of the possible responses of the system to a step of voltage: underdamped, critically damped, and overdamped.

Figure 9.1 — Galvanometric recorder.

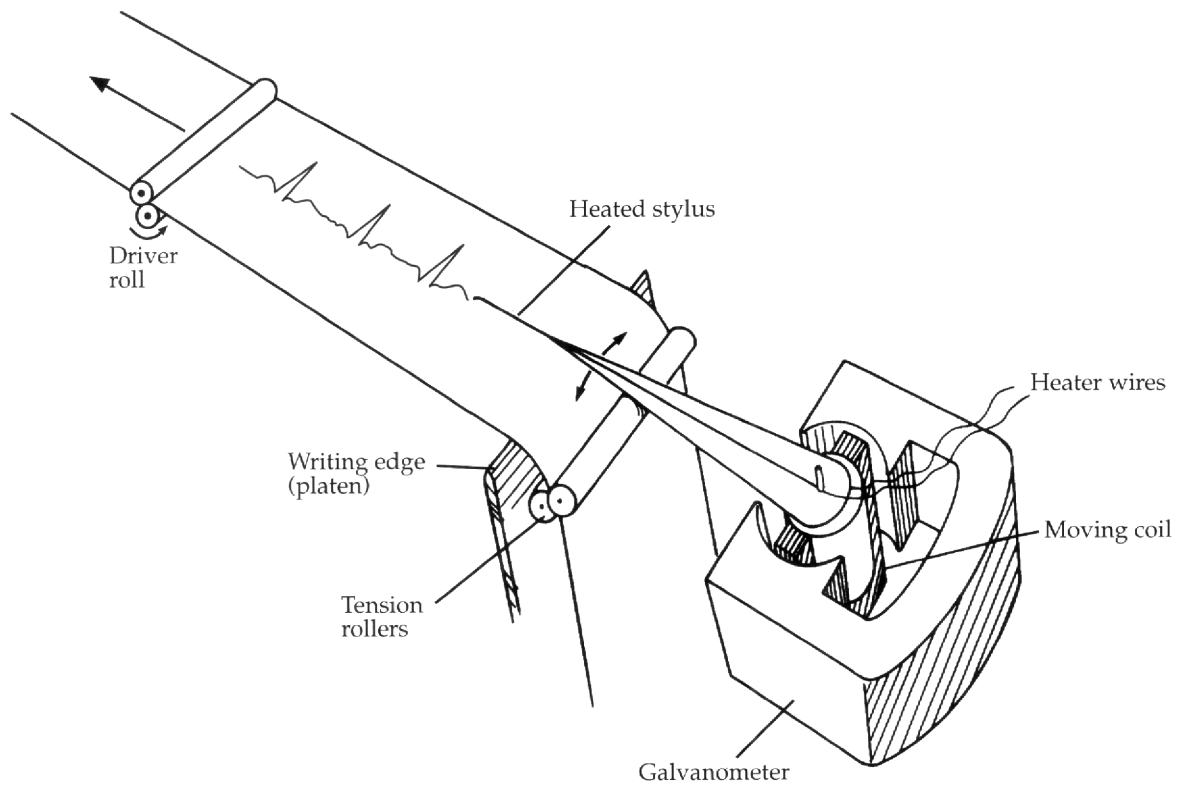


Figure 9.2 — Underdamped, critically damped, and overdamped responses to step input.

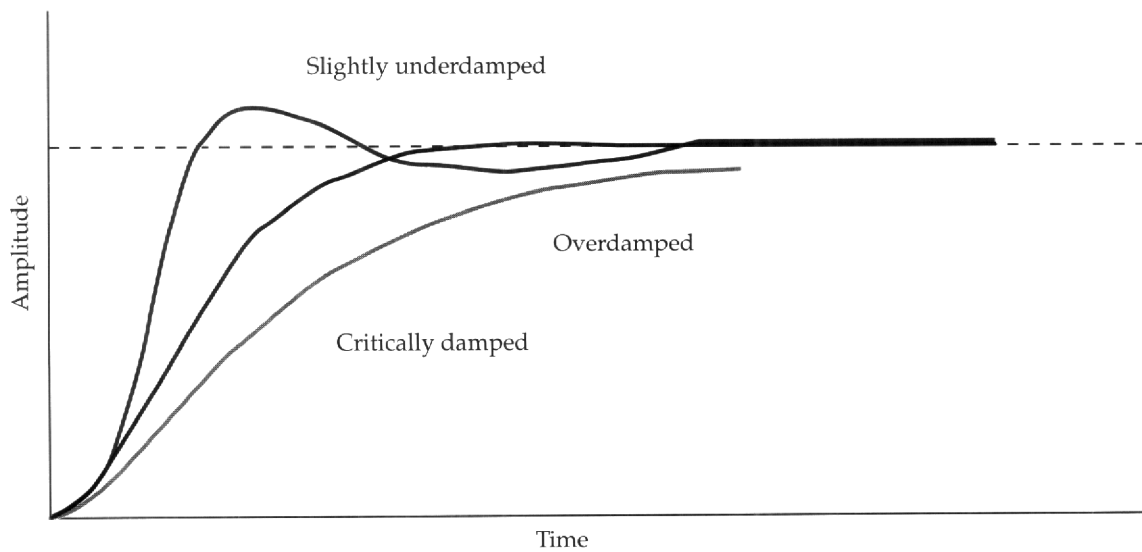


Figure 9.3 — Electrocardiographic paper showing times relative to 25 mm/sec.

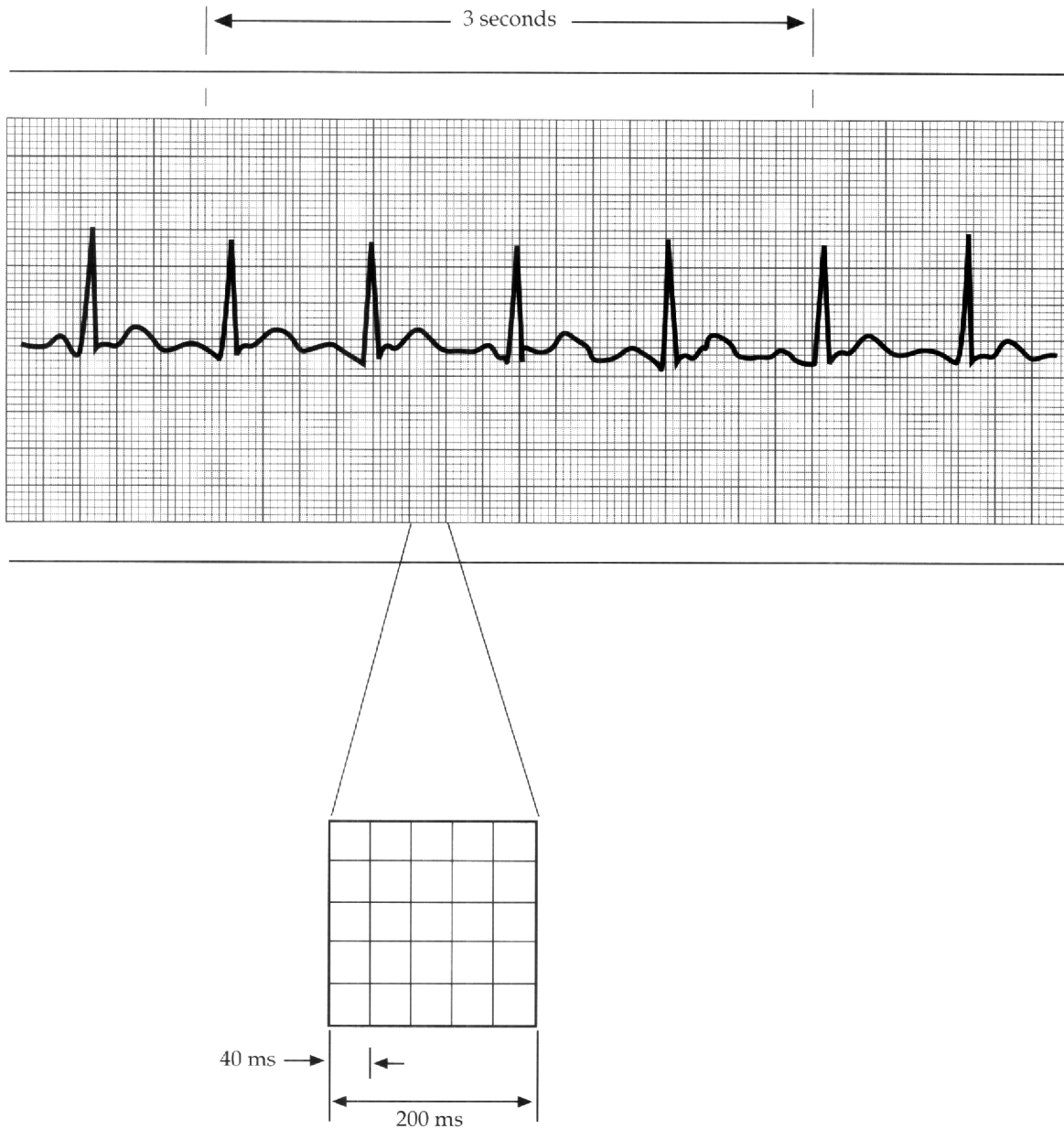
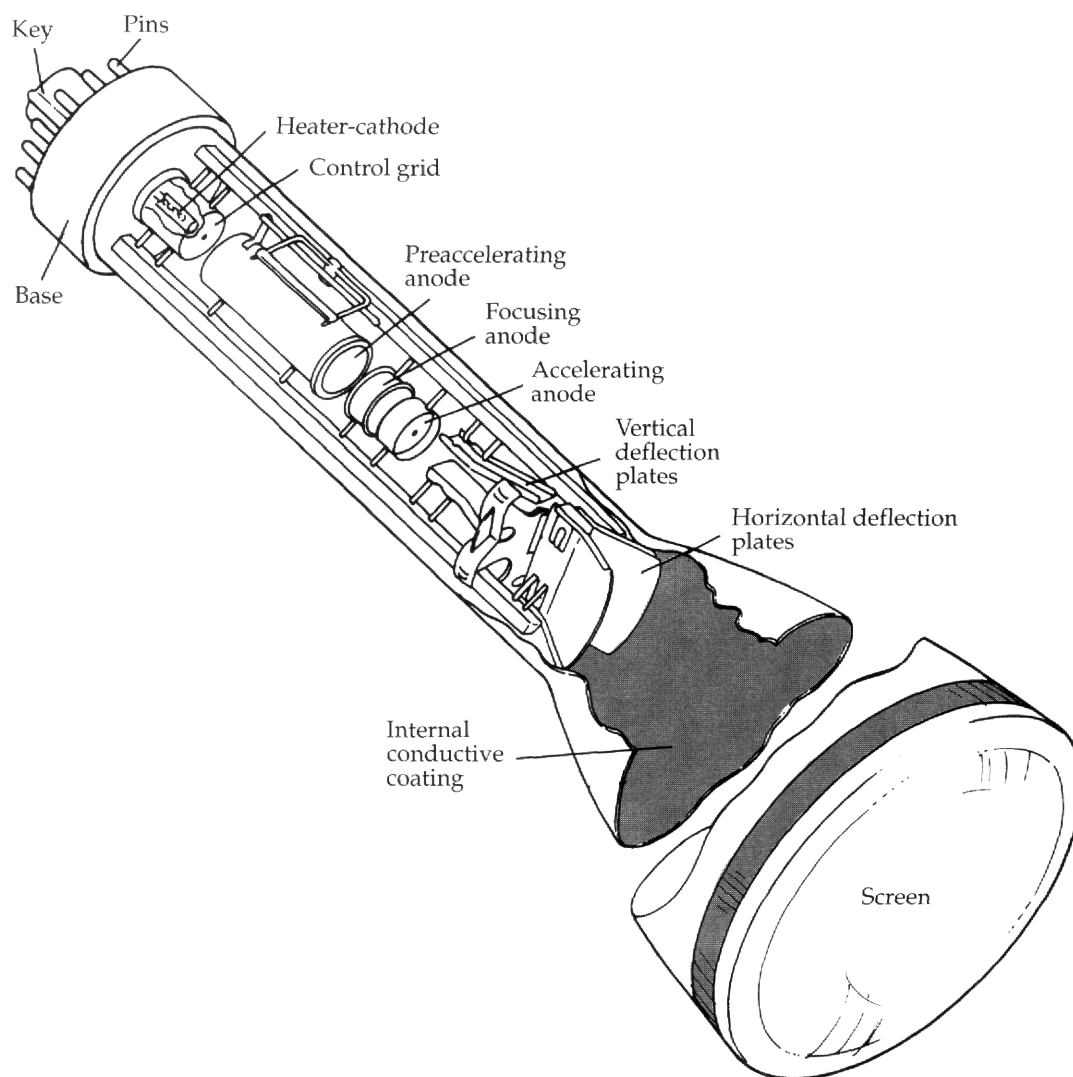


Figure 9.4 — Internal structure of a cathode-ray tube.



The type of response of an electrocardiograph becomes evident when a step of calibration voltage is applied. Pressing the calibrate button of a typical electrocardiograph, for instance, applies a 1-millivolt step of voltage to the amplifier. An underdamped system would produce a damped oscillation, which is often called ringing, at the top of the step. An overdamped system would be slow in reaching the top of the step. A critically damped system is theoretically possible but very difficult to achieve and maintain in practice. Several manufacturers clearly recommend adjustment of the damping control until the presentation shows very slight underdamping, that is, until the trace overshoots the top of the step by a barely perceptible amount. Readjustment is necessary after any event that

modifies the mass, spring "constant," or friction in the system. A change of paper, for example, can make readjustment of the damping control necessary because of the difference in smoothness of paper.

Keeping the paper taut at the writing edge and moving the paper at a constant velocity are two more requirements for accuracy in recordings. The standard speed of the paper in electrocardiography is 25 millimeters per second, which means that each millimeter represents 40 milliseconds. Between major divisions, which measure 5 millimeters, is 200 milliseconds. At the top of some paper, small marks denote 3-second intervals. Multiplying the number of complexes in 2 successive 3-second intervals by 10 gives the heart rate (Figure 9.3). Although the stylus, which moves through an arc, would normally produce a curvilinear trace, special designs of the stylus or writing edge enable the device to produce practically rectilinear, or pseudorectilinear, traces.

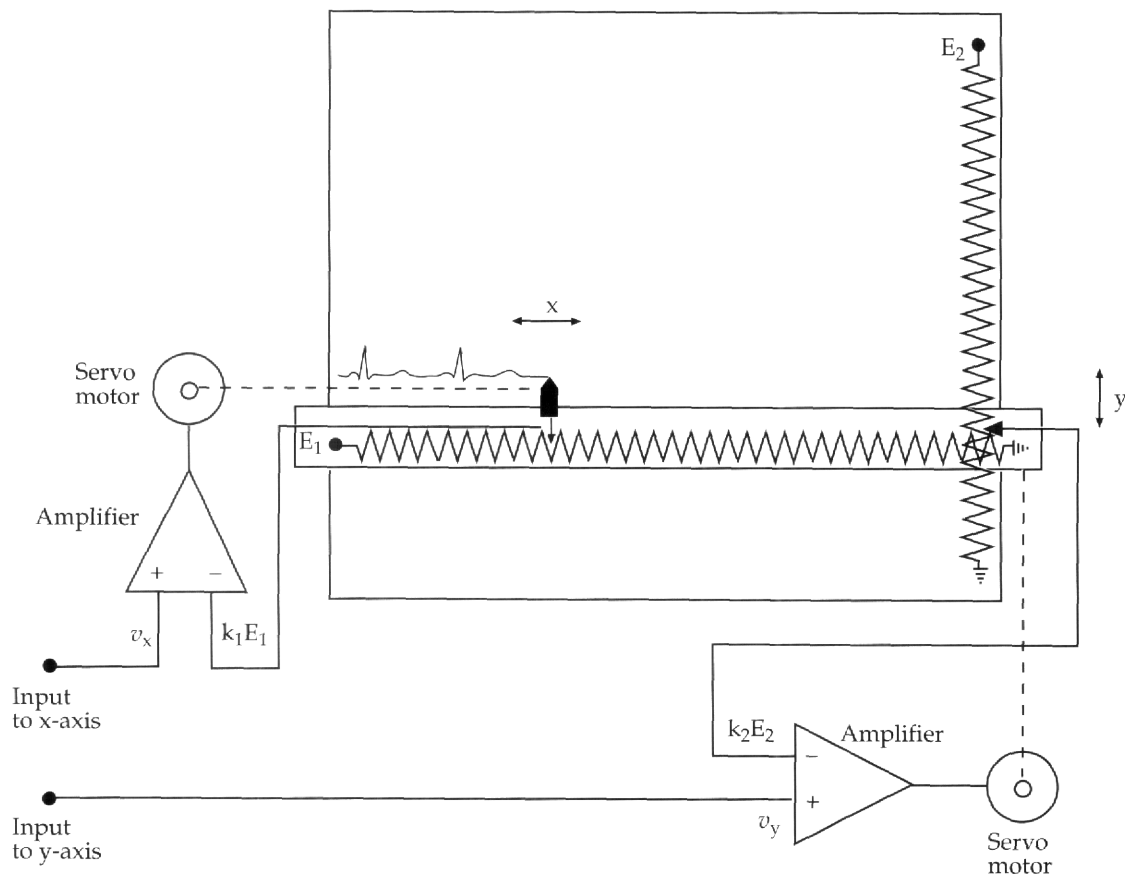
In a light-beam oscillograph, a mirror affixed to the moving coil replaces the stylus. A beam of light reflected from a fixed source to a moving photographic film produces the record, without some of the problems of the more common chart recorder.

9.3 ***Electronic Devices***

In electrocardiographic monitoring, the cathode-ray tube (CRT) has long been the display of choice. It provides a luminous display, but no permanent record unless a camera is used. Its presentation depends on the impact of a deflected stream of high-speed electrons on phosphorescent fluors deposited on the inside screen of the tube (Figure 9.4).

Electrons leaving the heated cathode accelerate because of electric fields produced by voltages on the anodes. Because the electrons acquire high velocity, they have high kinetic energy. A small fraction of that kinetic energy converts to light by way of the material deposited on the inside face of the tube. Fluorescence results while the electrons bombard the material; phosphorescence makes the glow persist for a short time, even after the beam of electrons has moved to a different spot. Adjustment of the electric fields can cause the electrons to converge to a tiny spot on the screen; the usual name of the process is electronic focusing. Deflection of the beam of electrons by electric fields causes vertical and horizontal movement of the spot on the screen, thereby creating a trace. The horizontal deflection usually depends on a linear voltage to move the beam at a constant velocity, while the vertical deflection depends on the amplitude of the applied signal.

Figure 9.5 — Functional diagram of an x-y recorder.



General-purpose oscilloscopes use a screen that has a persistence of glow much too short for presentation of biologic signals. The long-persistence material used in "slow screens," however, allows display of several complete complexes of the electrocardiogram. One nickname for a long-persistence display is "bouncing ball," because the luminous spot appears to bounce across the screen when tracing slow signals. Behind the bright, moving spot is a less luminous trail that fades in seconds. Variable-persistence oscilloscopes are available, but the complexity of the tube has limited their use in clinical medicine.

Most "non-fade" displays depend on refreshing the presentation periodically, using information from digital memory. Slightly displacing the signal at each sweep across the screen makes the display move, as if the signal were being presented in real time on a moving chart. To stop, or freeze, the signal on the screen, retracing from memory proceeds without the displacement.

An electronic display device that has a flat profile in contrast to the bulky one of a CRT involves liquid-crystal technology. Such a device, often called a liquid-crystal display (LCD), requires less space and power than a CRT. The typical LCD, however, has less contrast, resolution, and speed. A common application of LCDs is in portable electrocardiographs, because of the relatively small size and weight. Advancements in liquid-crystal technology, especially in regard to color displays, are likely to lead to applications in electrocardiography.

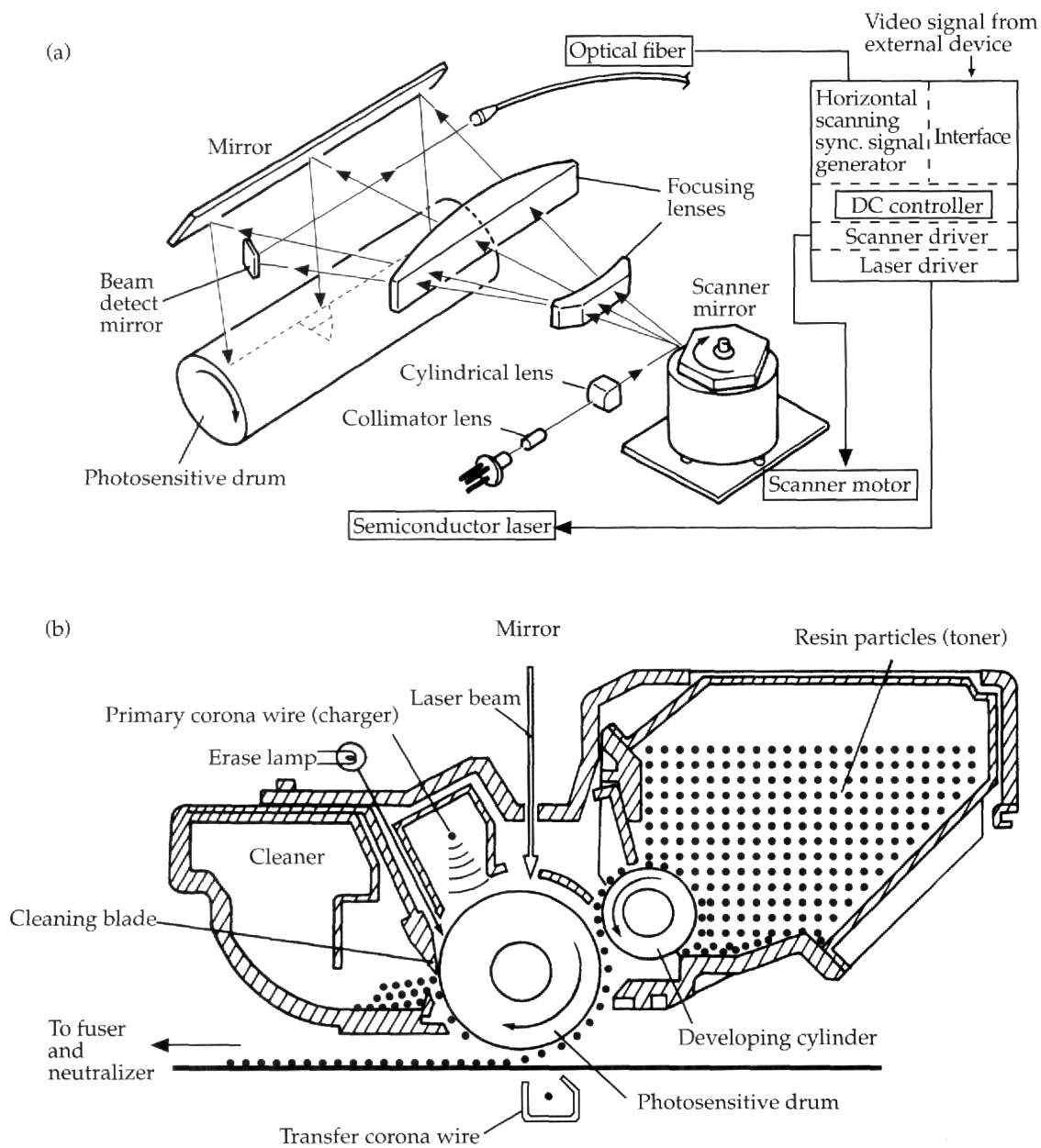
Color displays based on television technology allow presentation of several signals, each in a different color. In that kind of display, signals corresponding to pulses from an electronic pacemaker, for example, can appear in a hue that contrasts with that of the electrocardiographic trace, to help the observer evaluate the performance of the pacemaker. Alpha-numeric data, such as the patient's name, location, and attending physician, can be in yet another hue. Simultaneous presentation of annotated, color-differentiated traces provides for monitoring signals from several patients and for correlating signals of different phenomena from one patient. The presentation can include plots of serial data, or trend plots, with electrocardiographic and other signals.

9.4 ***Electronic Electromechanical Devices***

In this hybrid category is a device that inscribes an entire page of electrocardiographic leads from the memory of signals obtained immediately beforehand. One version of the device presents rows of signals along the 11-inch length of a standard page (8-1/2 inches by 11 inches). It inscribes several complexes of four standard leads in each of three rows, thus showing the twelve standard leads on one page. In the first column are leads I, II, and III; in the second column are aVR, aVL, and aVF. Leads V1 through V3 are in the third column, and leads V4 through V6 are in the fourth column. Near the bottom of the sheet is a long series of complexes of a selected lead. This series can serve as a rhythm strip.

The memory in the device is electronic, but the writer is electromechanical. The signal causes motors, acting through cables and pulleys or other linkages, to drive the stylus to positions disclosed to the electronic feedback circuit by transducers of horizontal and vertical displacement. When the stylus is in the correct position for the signal being presented, the outputs of the transducers are just enough to offset the signal. The stylus remains at that position until the signal changes and causes more

Figure 9.6 — Basic diagram of a laser printer: (a) Laser and mirror system; (b) Printing system.



movement of the stylus. The process continues until the trace is complete. Signals in digital format command movement of the stylus in some recorders, and the transduction in those recorders is digital too. Figure 9.5 presents a functional diagram of an x-y recorder, or plotter.

Another device in this category is the linear-array recorder in which paper moves beneath a linear arrangement of heaters or electrodes. In the thermal instrument, the marker is a column of tiny heaters. The thermally sensitive paper moves at constant speed while in contact with the column, and each energized heater creates a mark. The amplitude of the signal being recorded determines which heater is energized at a time. As the amplitude varies, the circuitry sends pulses to the appropriate heaters sequentially, causing a trace on the paper. The face of a typical heater, or thermal element, is very small; resolutions of 200 to 800 dots per inch are commercially available. In the electrostatic instrument, electrodes in a linear array relocate an electric field in response to the signal being recorded. The field polarizes the paper that moves under the electrodes. The charged portions of the paper attract particles of special ink, or toner, which bonds to the paper. A typical resolution is 200 dots per inch. The record produced by an electrostatic instrument is less susceptible to degradation by heat, pressure, and sunlight than the record produced by thermal-array recorders. Each type of instrument can produce a grid and alphanumeric characters as it traces the signal.

Yet another, but currently more costly, device in this category is a laser printer. The record does not emerge continuously while the signal is being traced, but emerges one page at a time. Each page can present electrocardiographic signals with other signals and with words and symbols the machine has been directed to print. The first step in producing the record is converting the information to digital code so that the record can be generated by turning a laser beam off and on in keeping with the binary basis of the code. The laser beam, reflected from a spinning system of mirrors, strikes the photosensitive drum that has a negative charge imposed when the drum rotates by the primary corona wire (Figure 9.6). The spinning mirror sweeps the continuously interrupted beam, by way of lenses and another mirror, across the drum. Spots on the drum struck by the laser beam become electrically neutral. As the drum rotates, new rows of neutral spots form in response to the pulses of laser light. The rows, or slices, are very thin, allowing the invisible pattern of spots to constitute the electrostatic image necessary for the next step: developing.

As the developing cylinder rotates, it magnetically obtains a coating of dark resin particles that contain bits of ferrite. The negatively charged particles, repelled by the negatively charged areas on the photosensitive drum, move to the spots that were made electrically neutral by the laser beam. (An alternate process is to charge the drum and particles so that particles go to the unexposed areas of the drum.) On the drum is the image that is attracted by the positive charge of the paper passing over the transfer corona wire. That image forms only part of a page of information because the circumference of the drum is less than the length of a standard sheet of paper. The drum continues rotating to allow a cleaning blade and an erase lamp to prepare it for recharging by the primary corona wire and for obtaining the next part of a page of information. The final steps in producing an entire page are neutralizing the charge on the paper and fusing the particles, or toner, onto the paper. A typical general-purpose machine has a resolution of 300 dots per inch, but much higher resolution is commercially available. The permanency of the record is essentially that of a page such as the one you are reading.

9.5 *Frequency Response*

The bandwidth of chart recorders is narrow relative to that of light-beam oscillographs and very narrow relative to that of oscilloscopes. A chart recorder strains while tracing a sinusoid signal of 100 hertz. A light-beam oscillograph can reliably show signals up to several thousand hertz, and an oscilloscope can display signals well into the megahertz range. Linear-array recorders, whether thermal or electrostatic, can record signals up to about 25 kilohertz. Each type of device can display steady, or dc, voltages.

Some electrocardiographs involve digital techniques for such tasks as filtering, compressing, transmitting, and storing. To allow comparison of such systems to purely analog systems, some manufacturers specify an equivalent analog bandwidth. Sampling rate and quantization are major considerations in designing a digital system capable of accurately representing an analog signal. Among other important considerations is the reason for the digital representation of the signal, whether for computerized evaluation of the signal or for generation of a display for human interpretation. Pertinent recommendations for digital display appear in a special report published by the American Heart Association.³⁰

10.0 MISCELLANEOUS CONCEPTS

10.1 *Cardiac Dipole*

An electric dipole exists ideally when two equal charges of opposite polarity and negligible mass and size are separated by a homogenous, isotropic medium (See Section 1.3). The electric field and the isopotential contours for that dipole are smooth and symmetric about an imaginary straight line drawn between the charges (Figure 1.2). One way to characterize the dipole is to fabricate a vector directed from the negative to the positive charge and accorded the magnitude of either charge multiplied by the separation. Any change in the electric field and isopotential pattern would change the vector's direction or magnitude, or both.

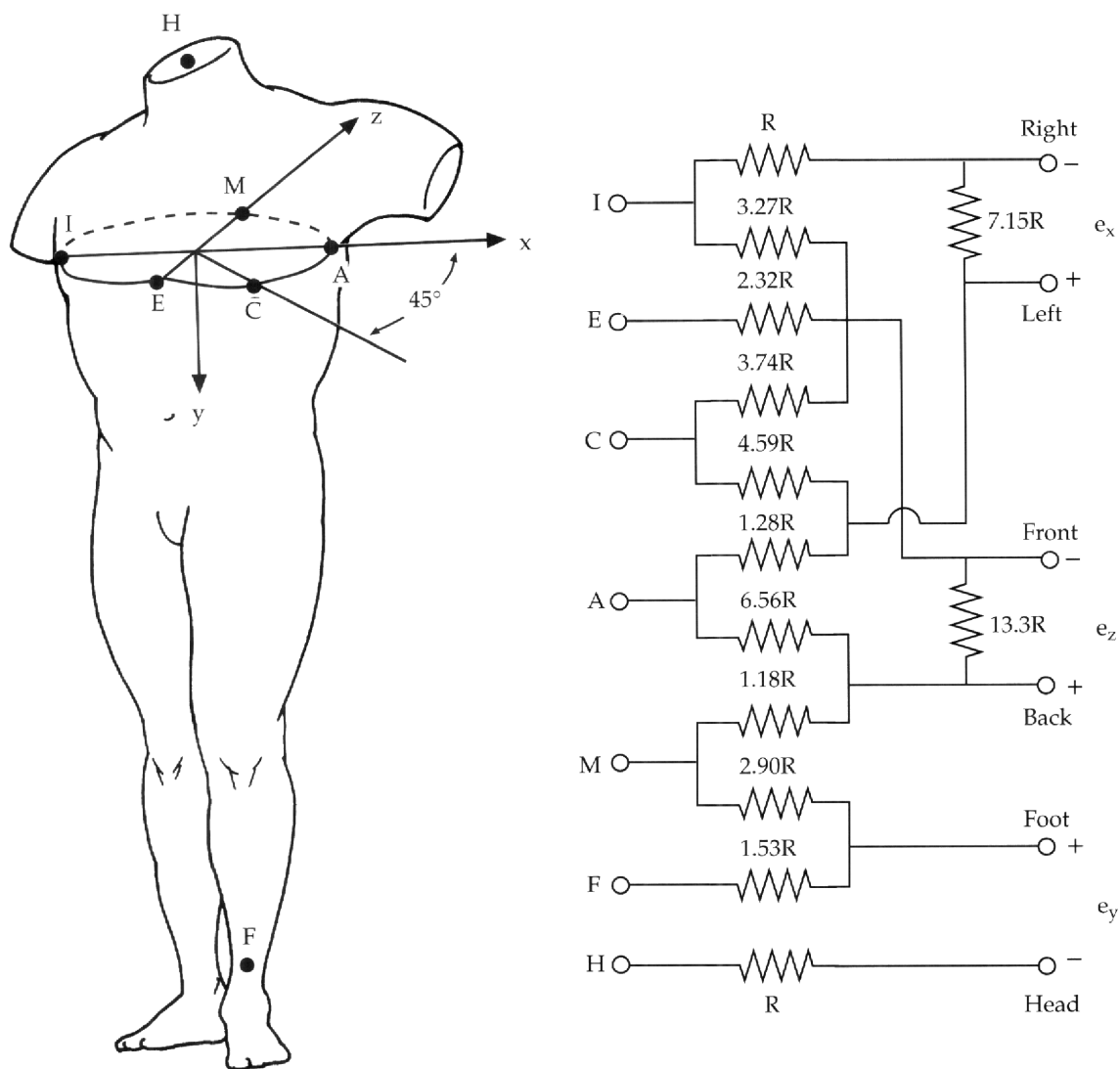
A single dipole is insufficient for characterizing the electric activity in the heart.^{31,32} At best, the cardiac dipole is an oversimplification that helps a person learn about cardiac excitation. At worst, it is an outdated attempt at a simple answer to a complex question, inadequate for analyzing all aberrations in electrocardiograms.

The wave of depolarization in the heart is a double layer, that is, a moving region in which positive charges are slightly separated from negative ones. In a figurative sense, the wavefront is a continuous array of dipoles. Resolution of all those dipoles into one provides an equivalent dipole. The corresponding vector must change in magnitude and direction as the wave moves through the heart. Depicting that vector at an instant requires a three-dimensional presentation or a set of two-dimensional pictures. Projection of the instantaneous vector onto various two-dimensional planes provides some information.

10.2 *Axis Deviation*

Mean electric axis is the term assigned to an average of all the instantaneous vectors relative to a portion of the surface electrocardiogram. The projection of that axis onto the frontal plane is the manifest electric axis. If the pertinent portion of the electrocardiogram is the QRS complex, the projection is the manifest QRS axis. Further elaboration of the concept involves a hexaxial reference system and the identification of states such as left-axis deviation.¹⁰ Among the causes of axis deviation are disease, age, diaphragmatic movements, body composition, and body position.

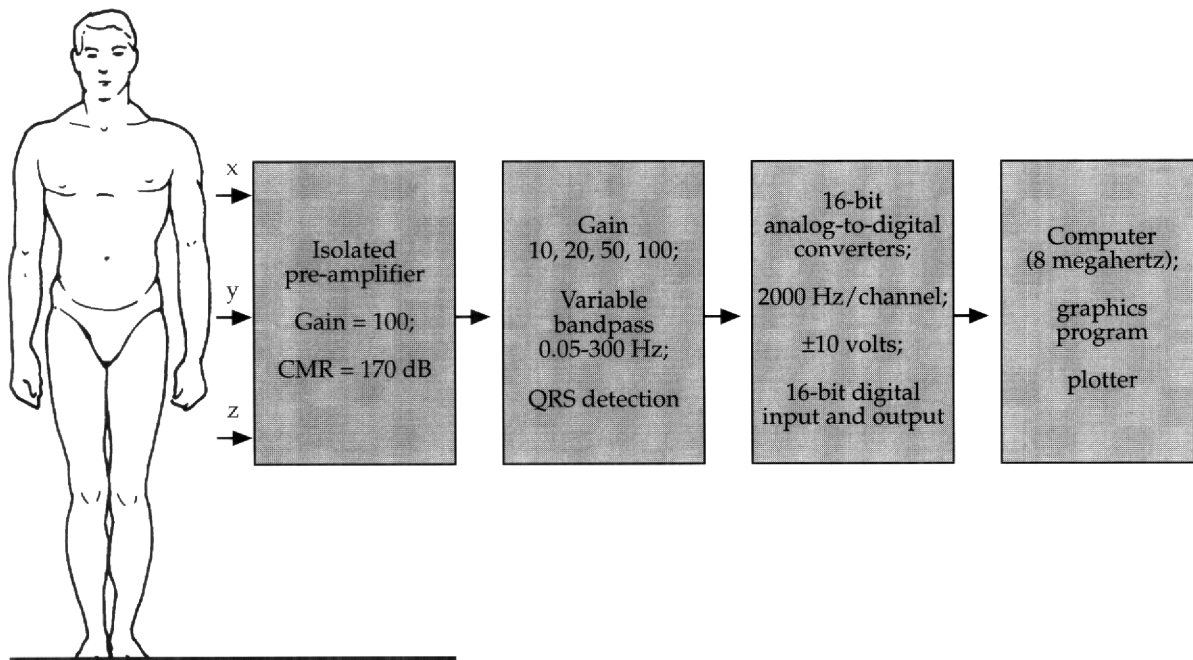
Figure 10.1 — Frank's vectorcardiographic system of leads.



10.3 Vectorcardiography

Unique definition of the cardiac vector would be possible by measuring three independent voltages if the dipole concept were truly applicable. To investigate, Frank used three orthogonal leads, x , y , and z , derived as shown in Figure 10.1. A study of the mean square error relative to several lead systems showed that the inaccuracy (13%) of the Frank system with 7 measuring electrodes was close to that (10%) of the standard system, with 9 measuring electrodes.³³ In that study, signals from 150 elec-

Figure 10.2 — Block diagram of a high-resolution electrocardiograph.



trodes, equally spaced anteriorly and posteriorly, provided the reference information. The error of a 30-electrode system with optimal placement was remarkably low (1%).

10.4 **High-Resolution Electrocardiography**

Amplifying the electrocardiogram more than usual while removing noise, or artifact, renders information that is normally obscured. The concept relates to removing maternal signals from a fetal electrocardiogram and to obtaining His-Purkinje signals from surface electrodes. Late potentials is the current term for the microvolt-level voltages that may occur toward the end of, or after, a QRS complex. Amplifying them requires prior reduction of the noise to obtain a suitable signal-to-noise ratio. Averaging the signal, often accomplished by a digital computer, can require several hundred complexes. Figure 10.2 shows the block diagram of a system for high-resolution electrocardiography.

11.0 INFORMATION FROM ELECTROCARDIOGRAMS

11.1 *Diagnostic and Prognostic Usefulness*

Conditions that alter the electric activity of the heart can cause visible abnormalities in the electrocardiogram. Data accumulated over years of electrocardiography allow linking the abnormalities to specific diseases and disorders. One reason for the popularity of the standard 12-lead system, despite its redundant signals, is the large amount of diagnostic information pertaining to that system.

Although the diagnostic value of electrocardiography is well established, the prognostic value remains debatable.³⁴ Relating electrocardiographic abnormalities to probabilities of sudden death from cardiac malfunction is still a challenge. An important objective of high-resolution electrocardiography is to identify persons likely to suffer ventricular tachycardia.³⁵

11.2 *Analysis*

Basic analysis of electrocardiograms involves measurement or study of rate, rhythm, and shape. The reason for presenting some of the terminology, techniques, and traces here is simply to emphasize the need for electrocardiographs capable of producing accurate traces.

11.2.1 Rate

The rate is simply the reciprocal of the period, which is the time between successive, like events. If the interval between consecutive R waves, for example, is 1 second, the instantaneous rate is 60 per minute. Insofar as the electric excitation signified by an R wave usually precedes a ventricular beat, the frequency of R waves is, conventionally, the heart rate. A malfunctioning heart may have two independent rates, an atrial one and a ventricular one. The reciprocal of the P-to-P interval is the atrial rate, which may be considerably different from that of the ventricles.

Sinus tachycardia is the condition in which the ventricular rate is higher than 100 beats per minute if the sinoatrial node is the origin of the excitations. It is one of the supraventricular tachycardias, which are

those caused by any pacemaker, normal or abnormal, above the bifurcation of the bundle of His. Another supraventricular tachycardia is atrial flutter in which the atrial excitation rate is usually 240 to 350 per minute. In atrial fibrillation, sometimes considered a supraventricular tachycardia, the rate is 350 to 600 per minute and irregular, hence its classification as an arrhythmia.

Ventricular tachycardia is the high heart rate of more than 120 beats per minute caused by a pacemaker, or ectopic focus, below the bifurcation of the bundle of His. Several definitions of the term specify that the high rate must persist for three or more ectopic, ventricular excitations. Ventricular tachycardia may warn that ventricular fibrillation, which is an immediate threat to life, may ensue.

The term bradycardia applies when the ventricular rate is below 60 beats per minute. Among the supraventricular types of slow rate is sinus bradycardia, common in athletes and present in some patients with acute myocardial infarction. Junctional bradycardia occurs when a part of the atrioventricular node assumes the role of pacemaker. Ventricular bradycardia exists when cells in the ventricles cause the slow pacing. Various degrees of block between the atria and ventricles can cause bradycardia, whether the block is organic or functional.

11.2.2 Rhythm

Rhythm is a patterned recurrence. Recurrence of the PQRST complexes in essentially the same shape at practically the same intervals denotes rhythm in the excitation of the heart. In a run of normal complexes, a complex arising because of an ectopic focus would disrupt the rhythm. An arrhythmia might arise from premature ventricular excitation (PVE), for example. Because a contraction would usually follow the excitation, the term premature ventricular contraction (PVC) has come into wider clinical use for the occurrence.

Atrial and ventricular fibrillation are extreme arrhythmias. The patterns and pertinent contractions are remarkably irregular. As the first four letters of the word fibrillation imply, fibers, or cells, cause the problem. The fibers seem to act independently, not in the normal, coordinated way; therefore, the heart fails to pump effectively. Ventricular fibrillation can lead to death in minutes. Atrial fibrillation, however, does not usually qualify as a cardiac emergency.

Figure 11.1 — Sequence for systematically reading electrocardiograms.

Stage I. The Rate

If normal-Proceed to Stage II.

If slow, why?

If rapid, why?

Stage II. The Rhythm

If regular-Proceed to Stage III.

If irregular, why?

Stage III. The Electric

Position of the Heart

If left axis deviation is present, why?

If right axis deviation is present, why?

Is there clockwise or counterclockwise rotation?

Stage IV. The P Wave

If normal-Proceed to Stage V.

If abnormal, why?

Stage V. The PR Interval and PR Segment

If normal-Proceed to Stage VI.

If abnormal, why?

Stage VI. The Q Wave

If normal-Proceed to Stage VII.

If abnormal, why?

Stage VII. The QRS Complex

If normal-Proceed to Stage VIII.

If abnormal, why?

Stage VIII. The QT Interval

If normal-Proceed to Stage IX.

If abnormal, why?

Stage IX. The ST Segment

If normal-Proceed to Stage X.

If abnormal, why?

Stage X. The T Wave

If normal-Proceed to Stage XI.

If abnormal, why?

Stage XI. The U Wave

Figure 11.2a — Abnormalities pertaining to stages of reading electrocardiograms.

Stage I. The Rate

If normal-Proceed to Stage II.

If slow

1. Sinus bradycardia.
2. Wandering pacemaker (or idioatrial or atrial escape rhythm).
3. Idioventricular rhythm.
4. Complete AV block.
5. SA block.
6. Atrial arrhythmias with high degrees of block.
7. Ventricular standstill.

If rapid

1. Tachycardias.
 - A. Sinus tachycardias
 - B. Idiofocal tachycardias.
 - a. Idioatrial.
 - b. Idionodal.
 - c. Idioventricular.
 - C. Paroxysmal tachycardias.
 - a. Idioatrial.
 - b. Idionodal.
 - c. Idioventricular.
 - D. Paroxysmal tachycardias.
 - a. Supraventricular.
 - i. Atrial.
 - ii. AV junctional.
 - b. Ventricular.
 - c. Reciprocating.
2. Ectopic beats.
3. Atrial flutter.
4. Atrial fibrillation.
5. Ventricular tachycardia.
6. Ventricular flutter.
7. Ventricular fibrillation.

Stage II. The rhythm

If regular-Proceed to Stage III.

If irregular

1. Sinus arrhythmia.
2. Ectopic beats.
 - A. Sinus.
 - B. Atrial.
 - C. AV junctional.
 - D. Ventricular.
 - a. Premature beats.
 - i. Extrasystolic beats.
 - ii. Capture beats.
 - iii. Reciprocal beats.
 - iv. Fusion beats.
 - v. Parasystolic beats.
 - b. Escape beats.
3. Sinus rhythm with SA block.
4. Wandering pacemaker.
5. Supraventricular rhythms with varying AV block.
 - A. Sinus rhythm.
 - B. Atrial tachycardia.
 - C. AV junctional tachycardia.
 - D. Atrial flutter.
6. Atrial fibrillation.
7. Sick sinus syndrome.
8. Ventricular flutter.
9. Ventricular fibrillation.

11.2.3 Shape

Shape refers to each wave, segment, and interval in an electrocardiogram. Although some of the shapes are more suggestive than indicative, each is worthy of scrutiny. A sharply peaked, or tented, P wave, sometimes called P pulmonale, for example, suggests that the abnormality in conduction results from pulmonary hypertension. Because the electrocardiogram is but a record of electrical events, attributing the abnormality of a wave to a mechanical condition may seem preposterous at first. A mechanical condition or event, however, sometimes affects the heart in a way that alters it electrically. Some abnormalities in the waves or intervals, including the segments, arise from a proximate cause that is electrochemical. Tall, peaked T waves, for example, may result from hyperkalemia.

11.2.4 Systematic Procedure

Many books on the interpretation of electrocardiograms offer analytic procedures, some involving devices such as specially marked scales, templates, and charts. The remarkably succinct procedure outlined in Figure 11.1 and related to diseases and disorders in Figure 11.2 (a through c) has 11 strictly sequential stages. Except for the third stage, which calls for determination of axis deviation, the systematic procedure involves the usual considerations of rate, rhythm, and shape.

11.3 *Closing Reminder*

The electrocardiograms of Figure 11.3 (a and b) demonstrate the wide ranges of rate, rhythm, and shape. Clear and accurate presentation of such signals depends on the equipment and technique. The equipment includes the electrodes, wires, cable, amplifier, and displayer. The technique includes the application of the electrodes, reassurance of the patient whose electrocardiogram is being taken, and adjustment of the controls of the electrocardiograph. If the equipment is properly designed, used, and maintained and if the technique is appropriate and effective, the presented signals will help clinicians arrive promptly at accurate diagnoses.

Figure 11.2b — Abnormalities pertaining to stages of reading electrocardiograms.

Stage III. The Electric Position of the Heart

If left axis deviation is present—Consider

1. Left anterior hemiblock.
2. Left ventricular hypertrophy.
3. Left bundle-branch block.
4. Wolff-Parkinson-White syndrome.
5. Antero-lateral peri-infarction block.
6. Right ventricular ectopic rhythms.
7. Mechanical shift of the heart.
8. Normal in 10 percent of the population.

If right axis deviation is present—Consider

1. Right ventricular hypertrophy.
 - A. Right bundle-branch block.
 - B. Left posterior hemiblock.
 - a. Inferior peri-infarction block.
 - b. Dextrocardia.
 - c. Left ventricular ectopic rhythms.
 - C. Children under 8 years of age.
 - a. Mechanical shift of the heart.
 - b. Normal variation.

Is there any rotation of the heart?

1. Clockwise rotation?
2. Counterclockwise rotation?

Stage IV. The P Wave

If normal—Proceed to Stage V.

If abnormal

1. Absent P waves.

<ol style="list-style-type: none"> a. AV junctional rhythm b. Idioventricular rhythm c. Atrial fibrillation. d. Atrial flutter. e. Sino-atrial block. f. Hyperkalemia. 	}	(unless there is visible retrograde conduction.)
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2. Distorted P waves.
 - a. P pulmonale.
 - b. P mitrale.
 - c. Wandering pacemaker.
 - d. Aberrant atrial conduction.
 - e. Variations in P-wave axis due to respiration.
3. Inverted P waves.
 - a. Dextrocardia.
 - b. AV junctional rhythm with retrograde conduction.
 - c. Ectopic beats and rhythms with retrograde conduction.
 - d. Incorrectly placed limb connections.
 - e. Physiologic.
4. Multiple P waves
 - a. AV block—partial.
—complete.
 - b. Blocked atrial premature beats.
 - c. Supraventricular tachyarrhythmias with AV block.

Stage V. The PR Interval and PR Segment

If normal—Proceed to Stage VI.

If abnormal

1. Prolonged PR interval due to first degree AV block caused by:
 - a. Drugs such as digitalis and beta-blockers.
 - b. Active carditis from any cause but especially rheumatic.
 - c. Hypokalemia.
 - d. Normal variant—rare.
2. Short PR interval.
 - a. Wolff-Parkinson-White syndrome.
 - b. Lown-Ganong-Levine syndrome.
 - c. AV junctional rhythm.
 - d. AV junctional beats.
 - e. Dissociated beats.
3. Varying PR interval.
 - a. Wenckebach phenomenon.
 - b. Wandering pacemaker.
 - c. Multifocal atrial premature beats.
 - d. Complete AV block.
 - e. AV dissociation.
4. Shifts in the PR segment.

Stage VI. The Q Wave

If normal—Proceed to Stage VII.

If abnormal

- a. Myocardial infarction.
- b. Pulmonary embolus.
- c. Right ventricular hypertrophy.
- d. Left ventricular hypertrophy.
- e. Left bundle-branch block.
- f. Cardiomyopathies.

Stage VII. The QRS Complex

If normal—Proceed to Stage VII.

If abnormal

1. Widening of the QRS complex.
 - a. Bundle-branch block.
 - b. Aberrant ventricular conduction.
 - c. Ventricular ectopic beats.
 - d. Ventricular parasystole.
 - e. Ventricular hypertrophy.
 - f. High serum potassium.
 - g. Quinidine.
 - h. Wolff-Parkinson-White syndrome.
2. Low-voltage QRS complex.
 - a. Hypothyroidism.
 - b. Pericardial effusion.
 - c. Chronic constrictive pericarditis.
 - d. Thick chest wall.
 - e. Myocardial infarction.
 - f. Incorrect standardization.
 - g. Emphysema.
3. High-voltage QRS complex.
 - a. Ventricular hypertrophy.
 - b. A thin chest wall.

Figure 11.2c — Abnormalities pertaining to stages of reading electrocardiograms.

4. Changes in shape of QRS complex.
 - a. Slurring in bundle-branch block.
 - b. Phasic aberrant ventricular conduction.
 - c. Ventricular ectopic beats.
 - d. Ventricular tachycardia.
 - e. Ventricular flutter.
 - f. Ventricular fibrillation.
 - g. Myocardial infarction.
 - h. Massive pulmonary embolus.
 - i. Variations in axis deviation.
 - j. Hyperkalemia.
 - k. Electric alternans.

Stage VIII. The QT Interval

If normal—Proceed to Stage IX.

If abnormal

1. Prolongation of the QT interval.
 - A. Prolongation of the QT interval (usually without symptoms).
 - a. Quinidine therapy.
 - b. Hypocalcemia.
 - c. Active rheumatic carditis.
 - d. Ventricular hypertrophy.
 - e. Diphtheritic heart disease.
 - B. Long QT syndrome.
 - a. Congenital causes.
 - i. Jervell and Lange-Nielsen syndrome.
 - ii. Romano-Ward syndrome.
 - b. Acquired causes
 - i. Drugs
 - a. Amiodarone.
 - b. Tricyclic antidepressants.
 - c. Lithium.
 - ii. Metabolic
 - a. Hypocalcemia.
 - b. Hypokalemia.
 - c. Hypomagnesemia.
 - iii. Ischemic heart disease.
 - iv. Mitral valve prolapse.
 - v. Autonomic nervous system dysfunction.
 - a. Following vagotomy.
 - b. Following carotid endarterectomy.
 - c. Central nervous system lesions.
 - d. Cerebrovascular accidents.
 - e. Head trauma.
 - f. Subarachnoid hemorrhage.
 - g. Cerebral tumors.
2. Short QT interval.
 - a. Digitalis.
 - b. Hypercalcemia.

Stage IX. The ST Segment

If normal—Proceed to Stage X.

If abnormal

1. Elevated ST segment.
 - a. Recent myocardial infarction.
 - b. Pericarditis.
 - c. Prinzmetal's variant angina.

- d. Cardiac trauma.
- e. Hyperkalemia.
- f. Ventricular aneurysm.
- g. African and Asian nationalities.
- h. Physiologic.
2. Depressed ST segment.
 - a. Ischemia.
 - b. Digitalis therapy.
 - c. Ventricular "strain" pattern.
 - d. Tachycardia.
 - e. Hypokalemia.
 - f. Ventricular hypertrophy.
 - g. Bundle-branch block.
 - h. Ectopic beats.
 - i. Cardiomyopathies.

Stage X. The T Wave

If normal—Proceed to Stage XI.

If abnormal

1. Tall peaked T waves.
 - a. Hyperkalemia.
 - b. In leads V2 and V3 after posterior myocardial infarction.
 - c. African and Asian nationalities.
2. Flattened T waves.
 - a. Myocardial ischemia.
 - b. Hypothyroidism.
 - c. Pericarditis.
 - d. Cardiomyopathies.
3. Inverted T Waves
 - a. Myocardial ischemia
 - b. Subendocardial infarction.
 - c. Pericarditis.
 - d. Hypokalemia.
 - e. Ventricular hypertrophy.
 - f. Cardiomyopathies.
 - g. Hyperventilation.
 - h. Associated with tachycardias.
 - i. After drinking iced water.
 - j. Following a meal or glucose.
 - k. Anxiety.
 - l. Infancy and childhood.

Stage XI. The U Wave

If normal—Ignore.

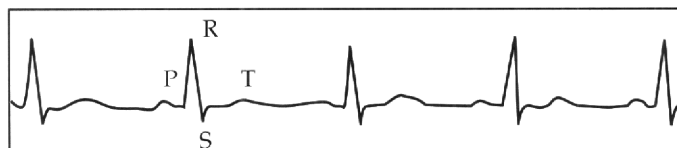
If abnormal

1. Prominent U wave.
 - a. Ventricular hypertrophy.
 - b. Bradycardia.
 - c. Hypokalemia.
 - d. Hyperthyroidism.
 - e. Digitalis.
 - f. Adrenaline overdosage.
 - g. Hypercalcemia.
2. Inverted U wave.
 - a. Hyperkalemia.
 - b. Ischemic heart disease.
 - c. Left ventricular "strain."

Figure 11.3a — Some electrocardiographic complexes to emphasize differences in rate, rhythm, and shape.

Normal sinus rhythm

Impulses originate at SA node at normal rate



All complexes evenly spaced; rate 60 to 100/minute

Sinus bradycardia

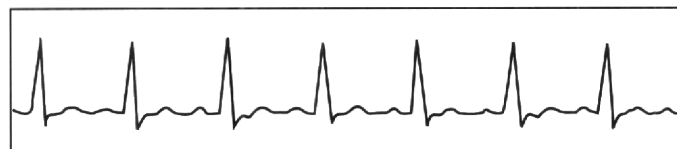
Impulses originate at SA node at slow rate



All complexes normal, evenly spaced; rate <60/minute

Sinus tachycardia

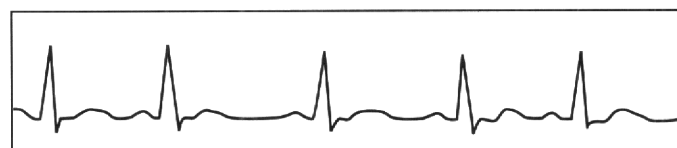
Impulses originate at SA node at rapid rate



All complexes normal, evenly spaced; rate >100/minute

Sinus arrhythmia

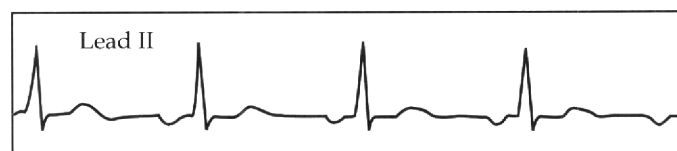
Impulses originate at SA node at varying rate



All complexes normal but rhythmically irregular. Longest PP or RR interval exceed shortest by 0.16 second or more

Nonsinus atrial (coronary sinus) rhythm

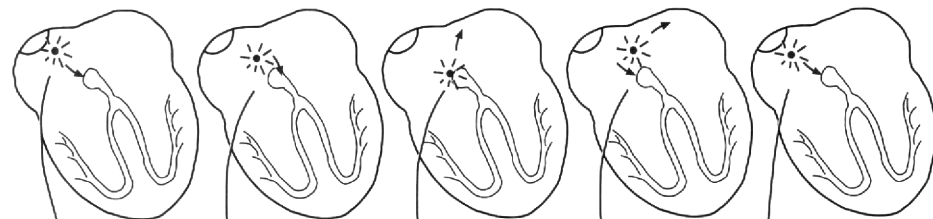
Impulses originate low in atrium; travel retrograde as well as distally



P waves inverted in leads II, III, and a VF

Normal sinus rhythm

Impulses originate at SA node at normal rate



Variations in P wave contour, PR interval, PP, and RR intervals

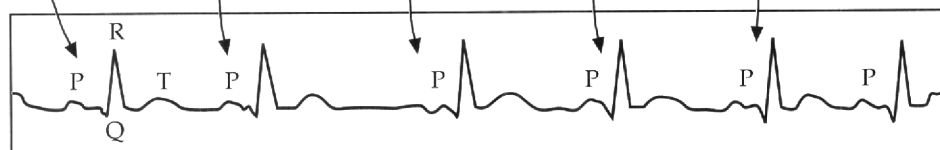
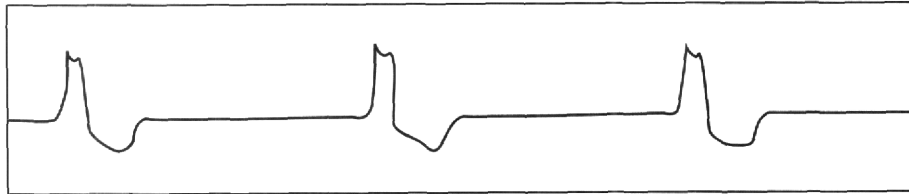


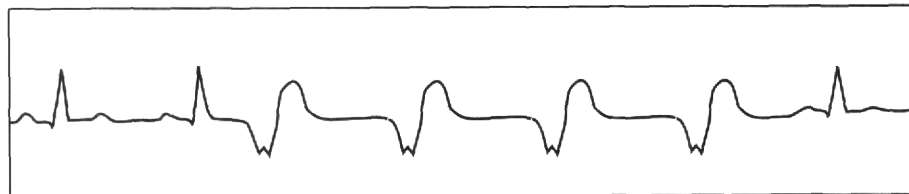
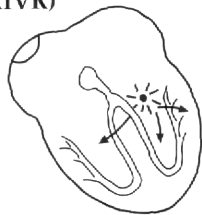
Figure 11.3b — Some electrocardiographic complexes to emphasize differences in rate, rhythm, and shape.

Idioventricular rhythm



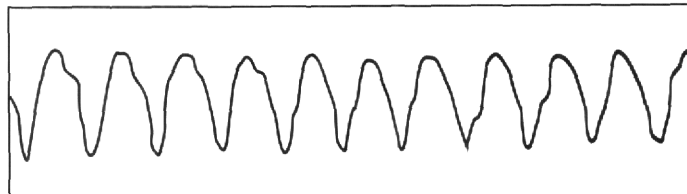
Rate < 40/minute

Accelerated idioventricular rhythm (AIVR)



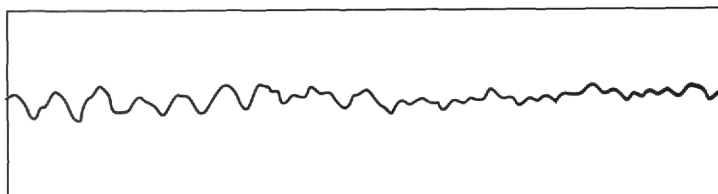
Rate 40 to 120

Ventricular tachycardia

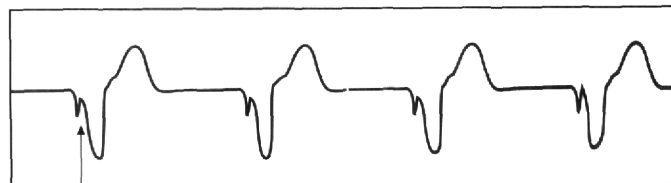
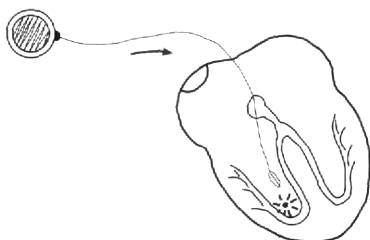


Rate > 120

Ventricular fibrillation



Pacer rhythm



Pacemaker spike

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Figure 2.1, 2.3, & 2.4

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Figure 2.5

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Figure 3.1

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Figure 4.1

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Figure 5.1

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Figure 9.6

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Figure 10.1

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15.0 GLOSSARY

Action potential – The varying difference in electric potential across the membrane of an active cell.

Artifact – An abnormal signal or structure produced by an external agency; see noise.

Atrioventricular node – A mass of specialized cells in the right atrium, medial to the right atrioventricular valve and continuous with the other atrial cells and with the atrioventricular bundle; often divided by electrophysiologists into three functional regions: the atrionodal (AN), the nodal (N), and the nodal-His (NH).

Atria – Plural of atrium (see definition below).

Atrium – In anatomy, a chamber allowing entrance to another structure or organ; in cardiac anatomy, one of the two upper chambers.

AV node – See atrioventricular node.

Axis deviation – The deflection of the electric axis to the left or right of the axis assumed normal.

Bandwidth – The range of frequencies at which a system operates within specifications.

Baseline wander – A drifting in the record of a signal; random and slow deviations from the reference line of a signal recorded with respect to time.

Bipolar esophageal electrocardiogram – A record of electric signals from the heart when the signals are obtained by two electrodes near the end of a tube maneuvered along the esophagus to a position very close to the heart.

Biopotential – The potential measured from a point in or on an organism, to a reference point infinitely distant; often used to mean biovoltage or biopotential difference.

Body-surface potential map – Also BSPM; a map of equipotential contours determined by measurements at many locations on the skin, usually on the chest and back.

Bradycardia – Also bradyrhythmia; an abnormal heartbeat of 60 or fewer beats per minute.

Capacitance – The proportionality constant relating the electric charge of a device that can store electric energy to the voltage across the two conductive elements of the device.

Cardiac – Of, near, or pertaining to the heart.

Cardiac sock – An elastic fabric in which electrodes are arrayed; used to obtain epicardial signals.

Cell membrane – Also plasma membrane; in biology, the very thin, semipermeable layer of molecules that separates the inner and outer regions of a cell.

Common-mode rejection – The absolute value of the ratio of the differential-mode voltage gain to the common-mode voltage gain of a difference amplifier; a quality factor relating to the capability of a difference amplifier to be insensitive to signals that are the average of those at the input while being very sensitive to signals that arise from the difference between those at the input.

Coulomb's law – A description of a basic phenomenon about electric charge: The force between two charged particles is directly proportional to the product of the charges and inversely proportional to the square of the distance between the charges.

Defibrillator – A device used in attempting to convert cardiac fibrillation to sinus rhythm by sending electric current through the heart.

- Dielectric** – A substance capable of conducting so little current that it is often considered nonconducting; the electrically insulating material in capacitors.
- Deviation index map** – A body-surface potential map that depicts the difference between the potential at each point and the average for that point on healthy persons.
- Diastole** – The dilation or period of dilation of a chamber of the heart.
- Dipole** – Any pair of electric charges, or magnetic poles, of equal strength but of opposite sign or polarity, separated by a small distance.
- Drift** – Slow, random variation from a setting, position, or attribute.
- Electric axis** – The instantaneous mean of all dipole vectors relative to a portion of the surface electrocardiogram.
- Electrocardiogram** – Also ECG and EKG; the signal traced by an electrocardiograph; used in diagnosing heart disease that modifies the electric activity of the heart.
- Electrocardiograph** – The instrument used for recording electric signals generated by the heart.
- Electrode** – An electric conductor through which a current enters or leaves a substance in contact with the electrode.
- Electrodynamics** – The movements of electrically charged particles; the branch of physics dealing with such phenomena.
- Electroencephalogram** – Also EEG; a record of the electric signals generated by the brain.
- Electrogram** – A record of electric signals obtained by electrodes placed inside the body, on or very close to the source of the signal.
- Electrolyte** – A substance that dissociates into ions in solution; an ion in solution; in electrophysiology, a medium containing ions that is used between the electrode and the subject to enhance electric conduction, such as a lotion containing water, salts, and other chemicals.
- Electromyogram** – A record of electric signals from muscle.
- Electrophoresis** – The motion of charged particles in an electric field; in medicine, the separation of ionizable components of substances by means of an electric field and a suitable medium.
- Electrostatics** – The physics of phenomena pertaining to stationary charges.
- Epicardial** – Upon or in contact with the heart.
- Equipotential** – Also isopotential; having the same potential.
- Esophageal** – Pertaining to the esophagus, the tubular structure connecting the throat to the stomach.
- Fibrillation** – Very rapid, repeated contraction of muscle fibrils, often leading to uncoordinated, essentially ineffective contraction of the entire muscle.
- Fibril** – A very small fiber; contractile filaments in a muscle fiber.
- Field** – In physics, a space in which the influence of a property can be determined, as in gravitational and electric fields.
- Fidelity** – The degree to which a system accurately reproduces or amplifies a signal.
- Fourier analysis** – A mathematical procedure for analyzing periodic waves; the determination of the constant term and the coefficient of each term in the infinite series including the sine and cosine components of a signal.
- Frank system** – A vectorcardiographic system designed by E. Frank (see Figure 10.1).
- Free-running rate** – The intrinsic, unmodified frequency of operation.
- Frequency** – The number of occurrences of a periodic process in a unit of time; in electricity, the rate of oscillation of alternation in an alternating current or voltage.
- Gain** – An increase in the power of a signal; the ratio of output to input, as of power, voltage, or current of an amplifier.
- Galvanometer** – A device for detecting or measuring small electric currents by deflecting a needle along a scale or a stylus on a paper.
- Gap junctions** – Locations, or openings, in the intercalated disks of fibers of the heart; contacts of low resistance between fibers of the heart.
- Half-cell potential** – In practical electrocardiography, the potential difference that arises when an electrode and an electrolyte are joined.
- Harmonic** – An integral multiple of the fundamental frequency.
- Hertz** – A unit of frequency equal to one cycle per second; abbreviated Hz.
- High-resolution electrocardiography** – The study or recording of electrocardiographic signals that have been amplified and filtered more than usual to render information usually obscured.
- His-bundle electrogram** – Also HBE; the record of signals obtained by electrodes near the bundle of His, or atrioventricular bundle.
- Humectant** – An agent or material that promotes retention of moisture.
- Impedance** – A measure of the total opposition to current in a circuit; the complex, or rectangular, notation of the resistive and the reactive components of the total opposition to sinusoidally alternating current, expressed in the frequency domain.
- Input impedance** – The impedance at the input of a device or system; the opposition a current would meet when entering a device or system.
- Intercalated disk** – A double, undulated membrane connecting one cell in the heart to another.
- Intracardiac** – Within the heart.
- Ion** – An atom or a group of atoms with electric charge.
- Iontophoresis** – The introduction, by means of electric field or current, of ions into tissue for diagnostic or therapeutic purposes.
- Kirchhoff's voltage law** – An expression of conservation and continuity; the algebraic summation of voltages around a closed loop equals zero.

- Late potential** – A highly amplified and filtered electrocardiographic voltage, usually toward the end of, or after, the QRS complex.
- Lead** – In electrocardiography, a signal; in electricity, a wire or other conductive medium.
- Linearity** – Closeness to a straight line; commonly used to describe a system that has an output directly proportional to the input.
- Line-frequency artifact** – Interference or electric noise from power lines.
- Manifest electric axis** – The projection of the mean electric axis onto the frontal plane.
- Mean electric axis** – The mean of all the instantaneous vectors of dipoles relative to a portion of the surface electrocardiogram.
- Membrane** – See cell membrane.
- Mitochondria** – Plural of mitochondrion (see definition below).
- Mitochondrion** – A microscopic body found in cells of almost all organisms, its enzymes converting energy in a cell.
- Myocardial ischemia** – Insufficient blood (therefore insufficient oxygen and glucose) in the muscle fibers of the heart, usually due to functional constriction or actual obstruction of a blood vessel.
- Myocardium** – The middle and thickest layer of muscle in the heart wall.
- Noise** – Any disturbance that obscures a signal or reduces its clarity or quality.
- Ohm's law** – A summary of the relations among voltage, current, and resistance whereby voltage equals the product of current and resistance.
- Pacemaker (cardiac)** – A cellular mass, normally the sinoatrial node, that depolarizes spontaneously and begins the process leading to contraction of the heart; an electronic device to control or to regulate the excitation of the heart.
- Parasympathetic nervous system** – The portion of the autonomic nervous system originating in the central and posterior parts of the brain and in the lower part of the spinal cord that, in general, inhibits or opposes the effects of the sympathetic nervous system.
- Pen motor** – A galvanometric device for inscribing a representation of small electric current by deflecting a stylus on a moving chart.
- Permeability** – The capability of allowing material to move through.
- Pill electrode** – A bipolar electrode made in the form of a pill, or small mass, that can be swallowed; used to obtain bipolar esophageal electrograms.
- Phosphor** – A substance that glows for awhile after being struck by radiation or high-speed electrons; in electronic oscilloscopes, the fluorophosphorescent material deposited on the inside of the face of the cathode-ray tube.
- Polarized** – Having one of two opposite attributes or tendencies; in physics, having either positive or negative charge, or having either north or south magnetism.
- Potential (absolute)** – The work needed to bring a unit positive charge from an infinitely distant point to another point.
- Potential difference** – The work required to move a unit positive charge from one point to another.
- Pseudorectilinear** – Pertaining to "falsely straight" lines; a device or system for converting angular motion to linear motion or angular motion to linear display, as in some chart recorders.
- Purkinje network** – The immature muscle fibers at the end of the specialized conductive system of the heart; the widespread group of fibers in the ventricular subendocardium.
- Refractory period** – Also absolute refractory period; the interval during which a cell cannot be stimulated.
- Relative refractory period** – The interval during which a cell can be stimulated but only if the stimulus is stronger than a normal stimulus.
- Repolarization** – In physiology, the relocation of some cellular ions to reestablish the transmembrane voltage of the resting cell, with negative polarity at the inside of the membrane.
- Radio-frequency choke** – A coil or group of coils providing inductance to greatly impede high-frequency current.
- SA node** – Also S-A node; sinoatrial node (see definition below).
- Selective permeability** – The capability of allowing the passage of certain substances while impeding the passage of others.
- Sensing catheter** – A small, flexible tube or cylindrical solid with one or more electrodes at the end and conductors in the interior; used to obtain signals from inside the body, as in His-bundle electrography.
- Sinoatrial node** – A mass of cells in the right atrium, near the entrance of the superior vena cava; often called the pacemaker of the heart because electric activity in this node normally begins the process leading to contraction of the heart.
- Sinus-node electrogram** – Also SNE; a record of the signal obtained by intracardiac electrodes placed near the sinoatrial (SA) node.
- Slew rate** – The rate of change in the output of an amplifier with a large signal at the input.
- Slow screen** – In electronic oscilloscopes, the screen of a cathode-ray tube that has phosphors that glow long enough for low-frequency signals to be seen completely.
- Surfactant** – An agent or substance that lowers surface tension, or "makes water wetter," used in some electrolytes to help lower the resistance between the subject and the electrode.
- Systole** – The contraction, or period of contraction, of the heart or one of its chambers.
- Tachycardia** – Also tachyrrhythmia; rapid heartbeat; often used in classifying rates of 100 or more beats per minute.

Transient – In electricity, a transitory entity, such as the voltage that exists for a very short interval when a circuit containing reactive components is suddenly energized.

Transconductance gain – The ratio of the output current to the input voltage of an amplifier.

Vectorcardiography – The study or generation of displays of elliptical forms or figures representing the projection of the movement of the positive end of the cardiac dipole onto different planes, usually during a specific portion of the electrocardiogram.

Ventricle – A cardiac chamber that receives blood from the corresponding atrium and from which blood is forced into arteries.

Voltage – Potential difference; usually given in volts.

Wave – In depolarization, the advancing excitation; in electrocardiography, an identifiable deviation or excursion from the baseline.

Welch cup – Also suction-cup electrode; a type of electrode that is kept in place by suction produced by squeezing the elastic bulb.

Wilson central terminal – A contrived point of reference for each of the six signals obtained on the chest in standards, 12-lead electrocardiography.

Wolff-Parkinson-White syndrome – Also preexcitation syndrome; a concurrence of electrocardiographic signs of abnormality in the electric activity of the heart; visible in electrocardiograms of some patients with paroxysmal tachycardia.

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